



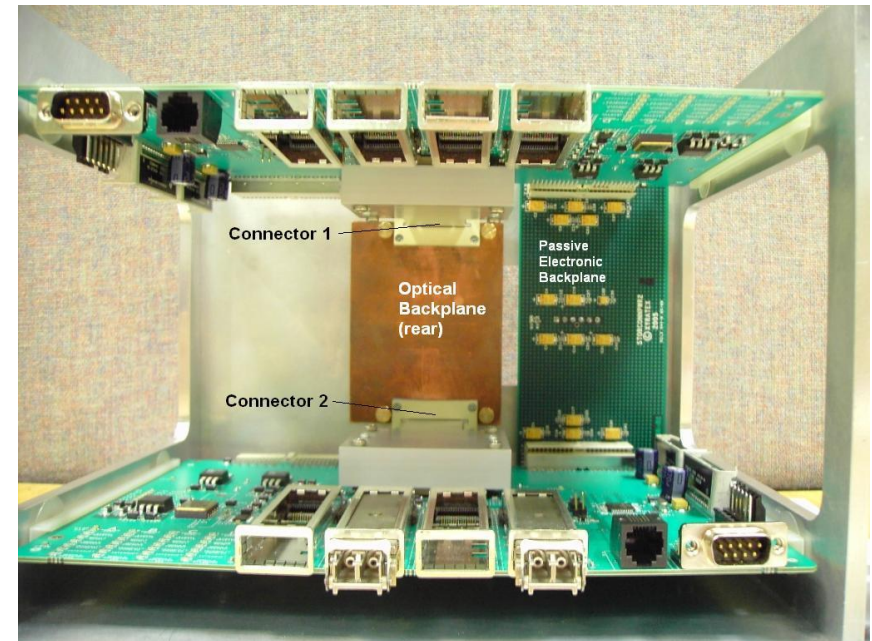
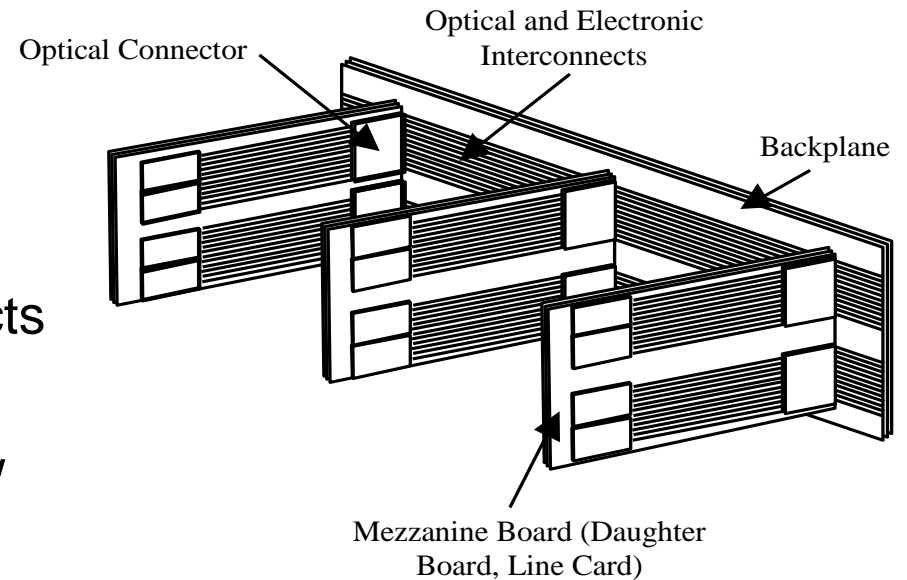
Integrated Waveguides

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Outline

- Electronic versus Optical interconnects
- The OPCB project
- OPCB University Research Overview
 - Heriot Watt
 - Loughborough
 - UCL
- System Demonstrator



Copper Tracks versus Optical Waveguides for High Bit Rate Interconnects

- Copper Track
 - ❑ EMI Crosstalk
 - ❑ Loss
 - ❑ Impedance control to minimize back reflections, additional equalisation, costly board material

- Optical Waveguides
 - ❑ Low loss
 - ❑ Low cost
 - ❑ Low power consumption
 - ❑ Low crosstalk
 - ❑ Low clock skew
 - ❑ WDM gives higher aggregate bit rate
 - ❑ Cannot transmit electrical power

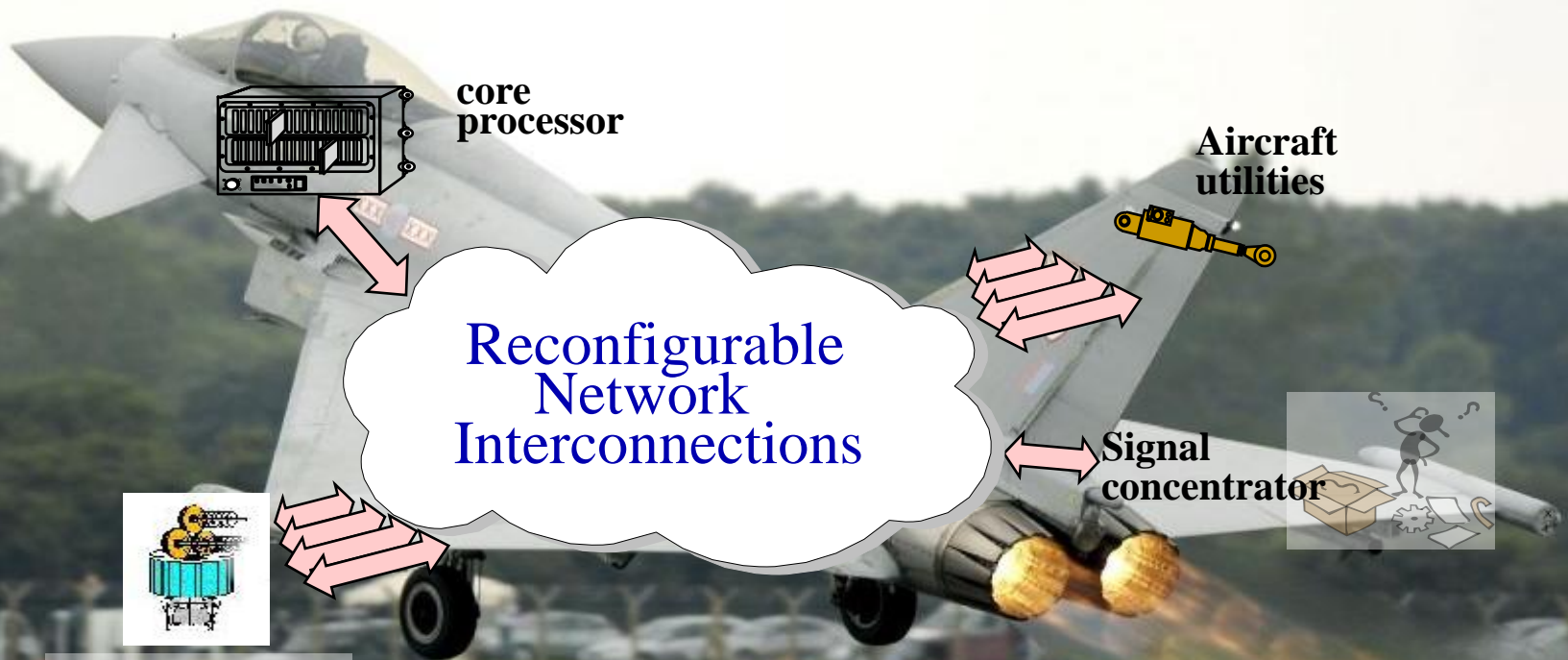
On-board Platform Applications

BAE SYSTEMS



On-board Platform Applications

BAE SYSTEMS

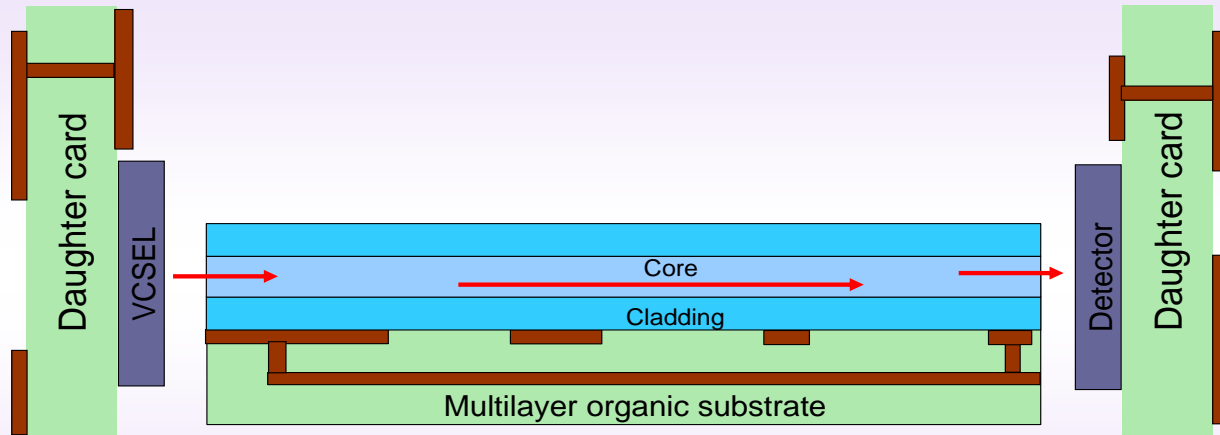


High Bandwidth Signals

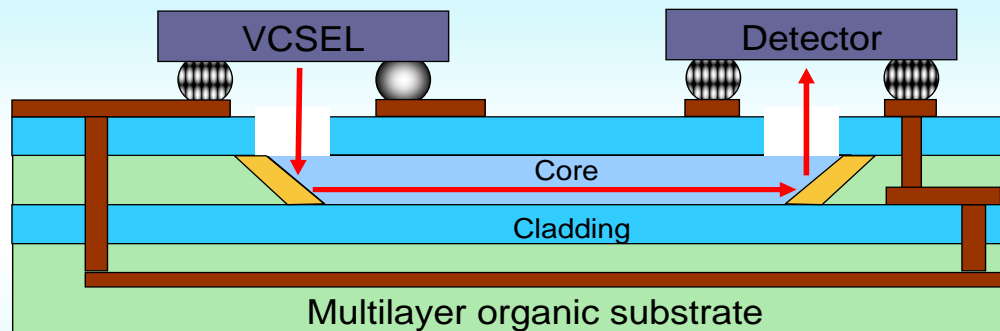
The Integrated Optical and Electronic Interconnect PCB Manufacturing (OPCB) project

- Hybrid Optical and Electronic PCB Manufacturing Techniques
- 8 Industrial and 3 University Partners led by industry end user
- Multimode waveguides at 10 Gb/s on a 19 inch PCB
- Project funded by UK Engineering and Physical Sciences Research Council (EPSRC) via the Innovative Electronics Manufacturing Research Centre (IeMRC) as a Flagship Project
- 3 year, £1.6 million project

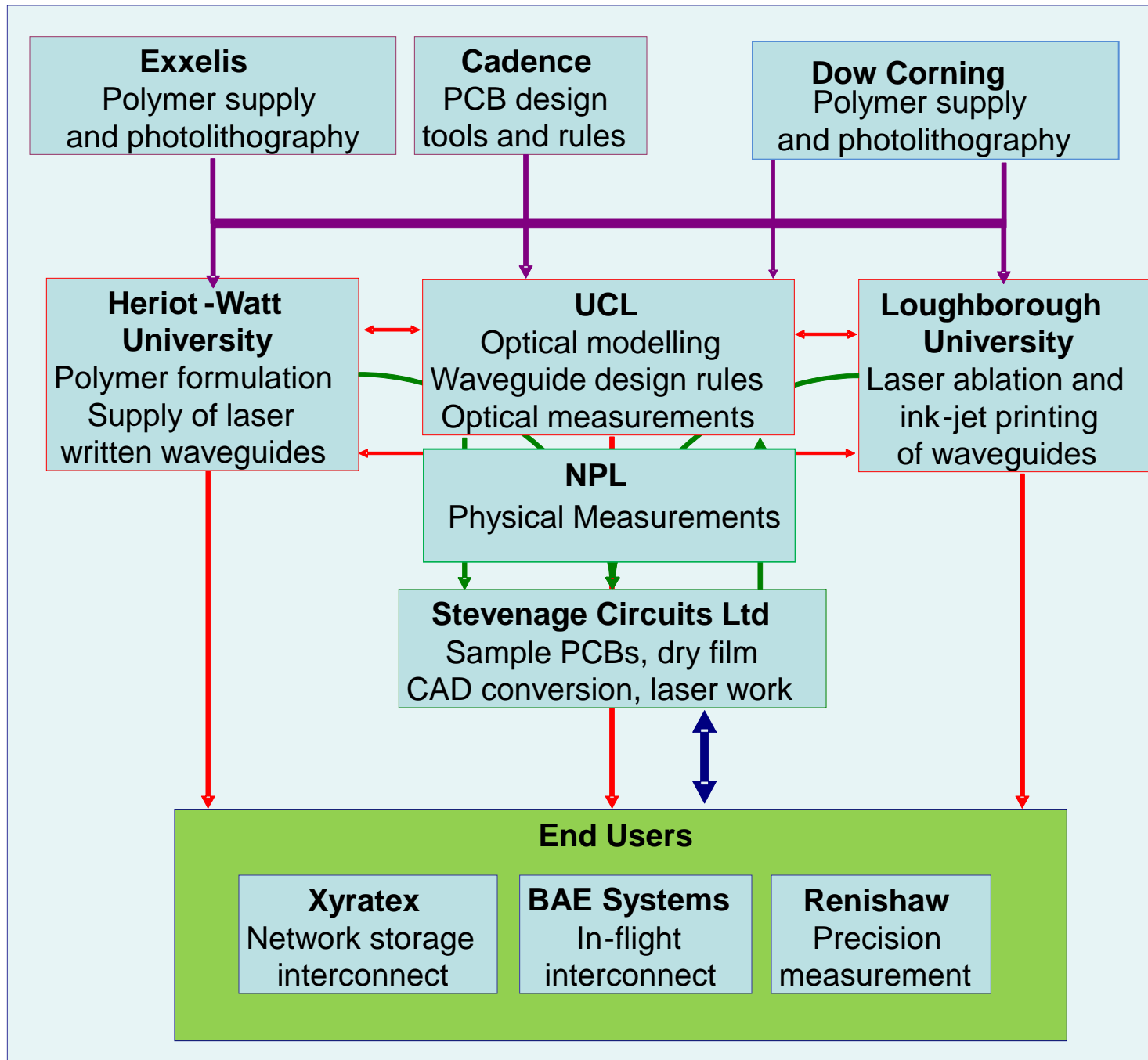
Integration of Optics and Electronics



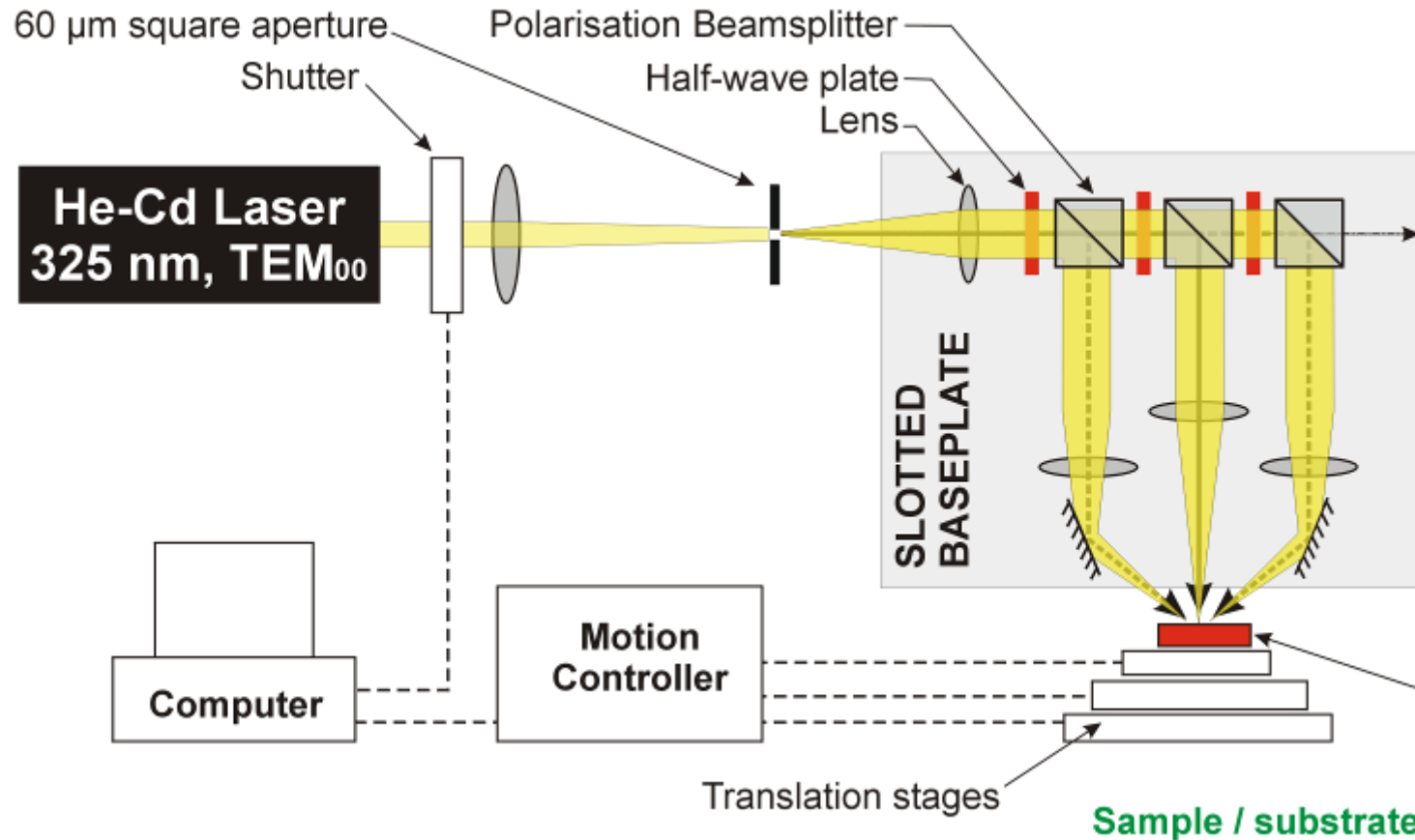
- Backplanes
 - Butt connection of "plug-in" daughter cards
 - In-plane interconnection
- Focus of OPCB project



- Out-of-plane connection
 - 45 mirrors
 - Chip to chip connection possible



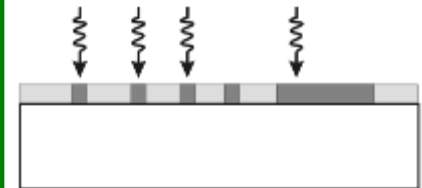
Direct Laser-writing Setup: Schematic



1: APPLY POLYMER TO SUBSTRATE



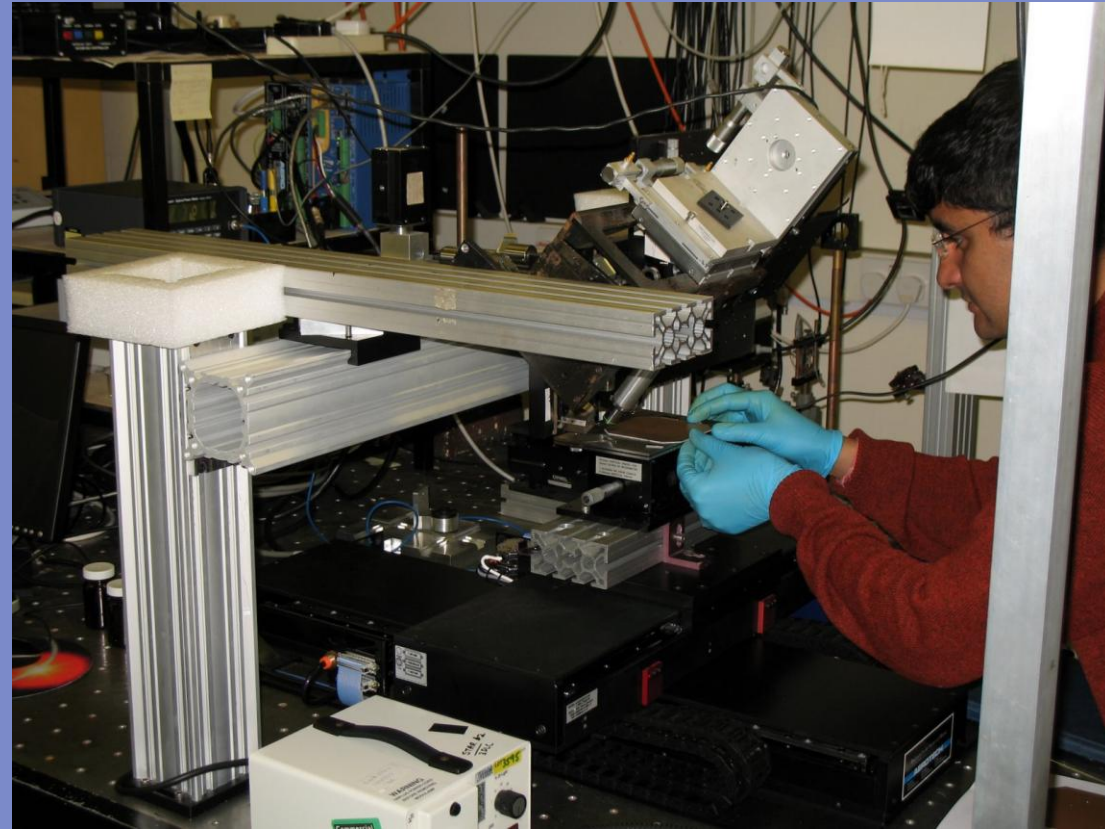
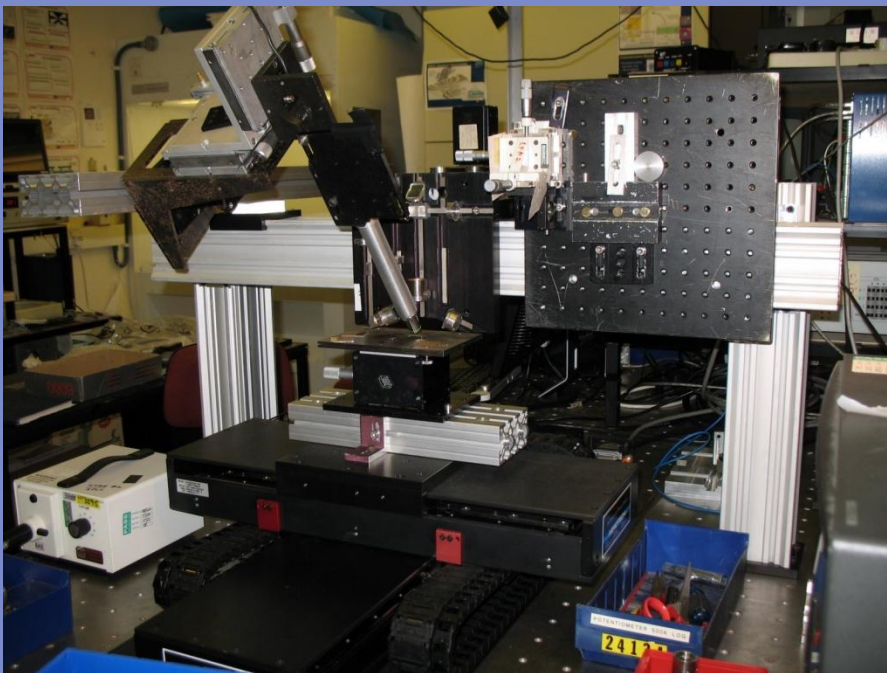
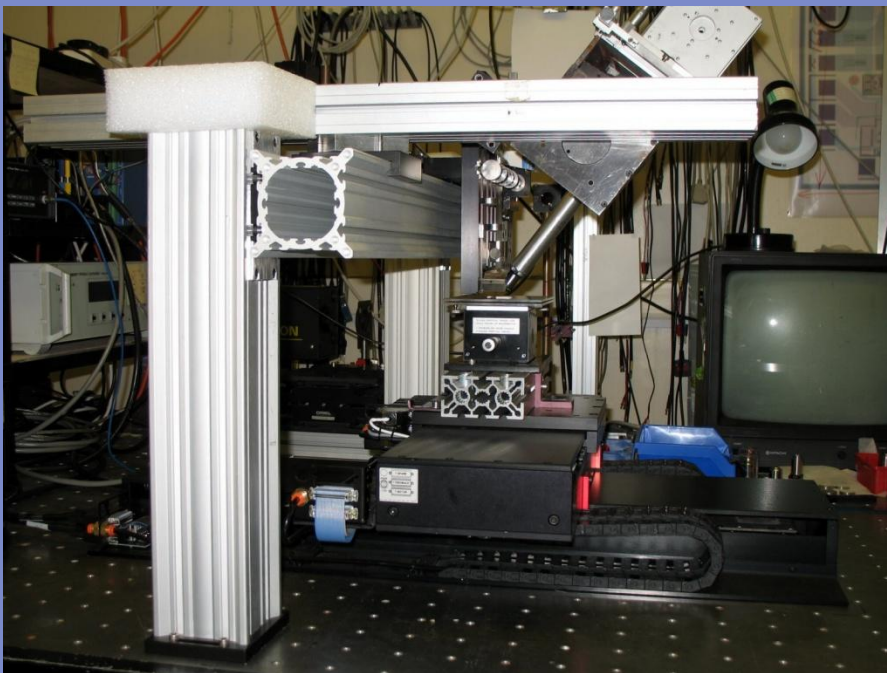
2: LASER WRITE STRUCTURES



3: DEVELOP POLYMER



- **Slotted baseplate** mounted vertically over translation, rotation & vertical stages; components held in place with magnets
- By using two opposing 45° beams we minimise the amount of substrate rotation needed

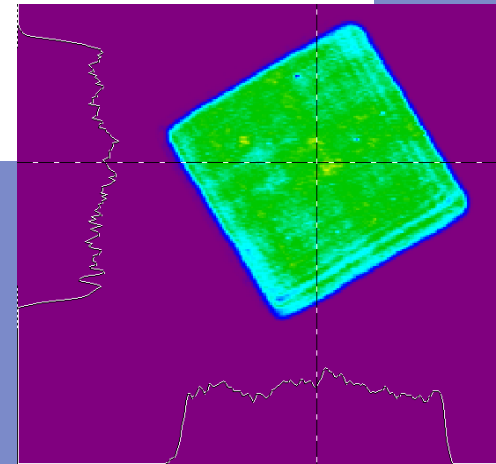
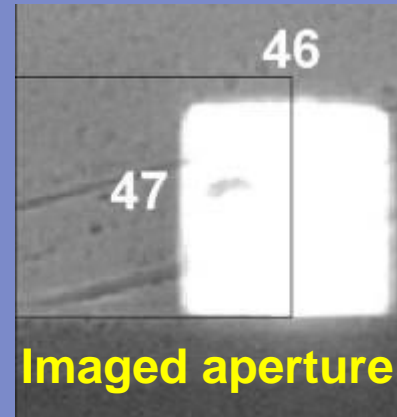
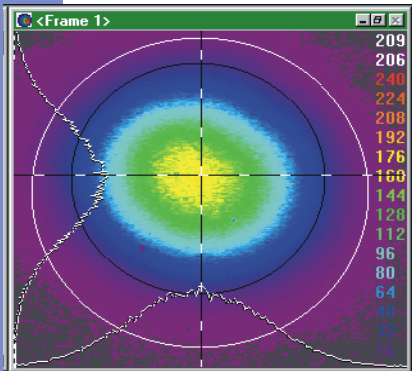
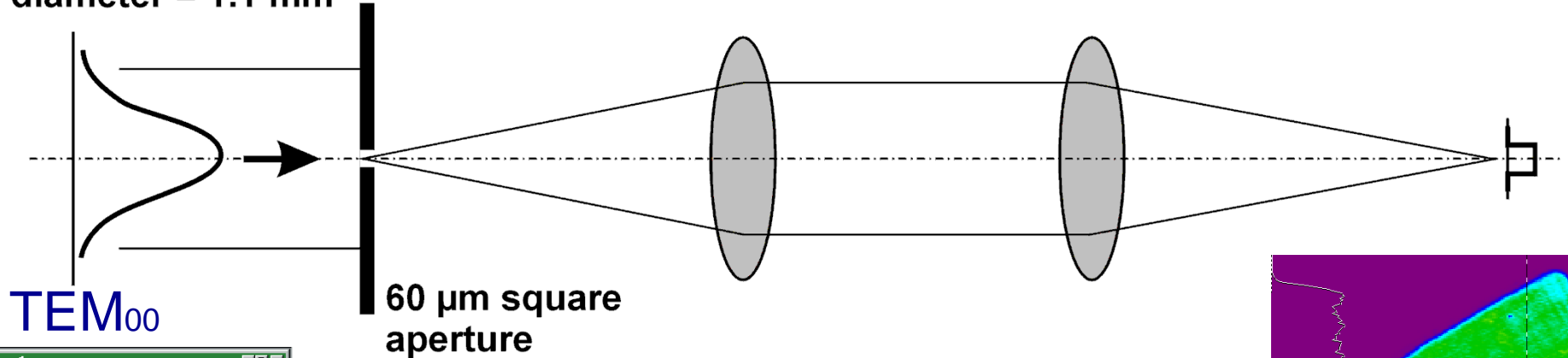


Writing sharply defined features

– flat-top, rectangular laser spot

Gaussian beam
diameter = 1.1 mm

Imaging system / lenses

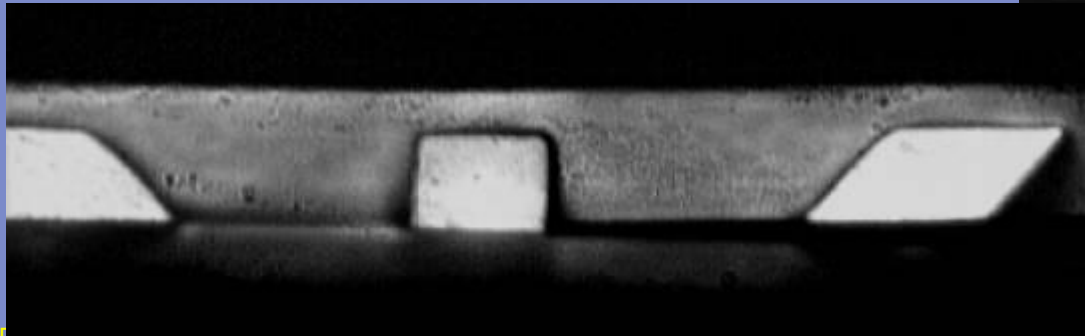
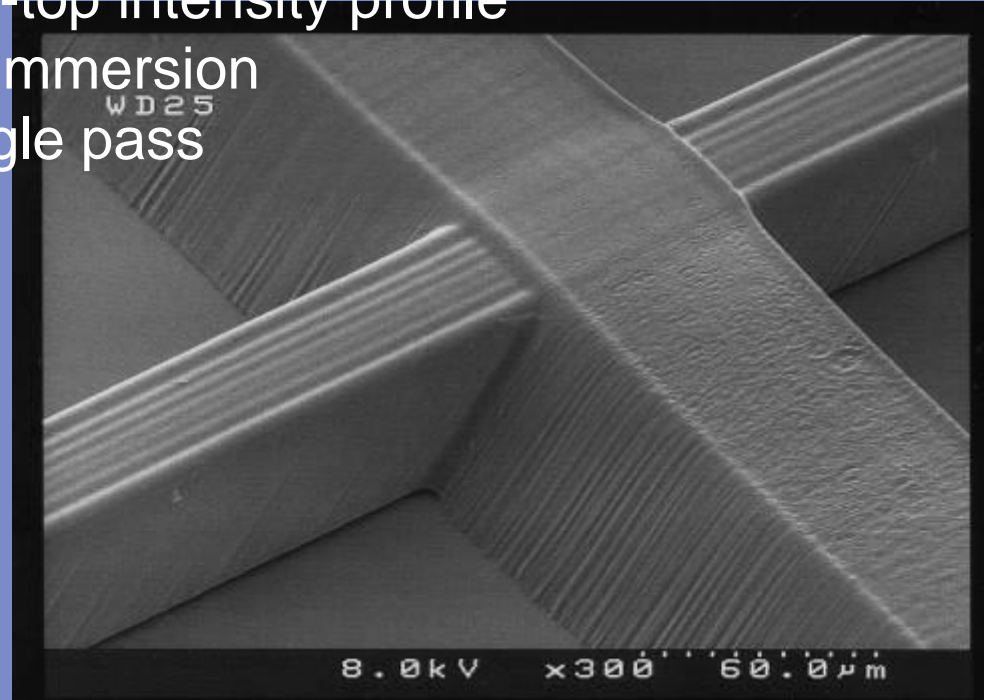
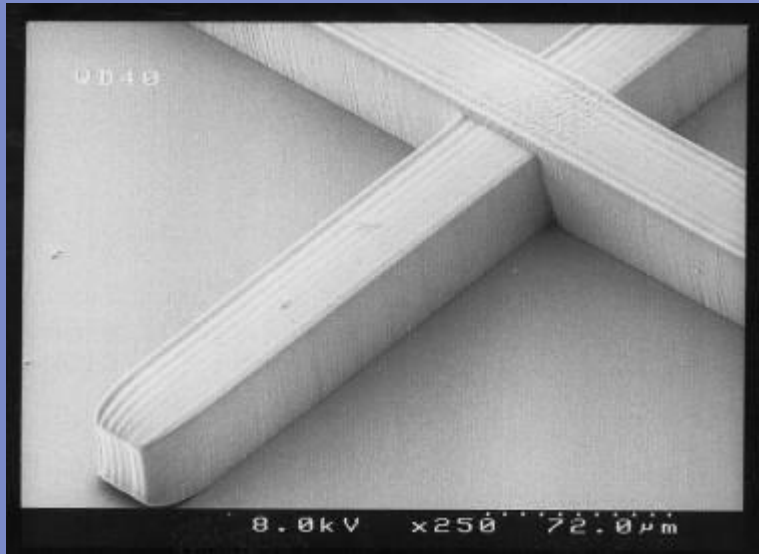


Images of the resulting waveguide
core cross-sections

Laser written polymer structures

SEM images of polymer structures written using imaged 50 μm square aperture (chrome on glass)

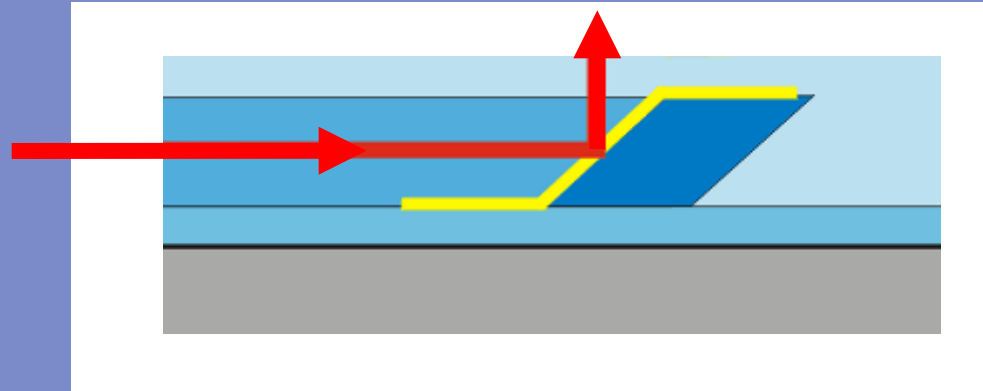
- Writing speed: $\sim 75 \mu\text{m} / \text{s}$
- Optical power: $\sim 100 \mu\text{W}$
- Flat-top intensity profile
- Oil immersion
- Single pass



Optical microscope image showing end on view of the 45° surfaces

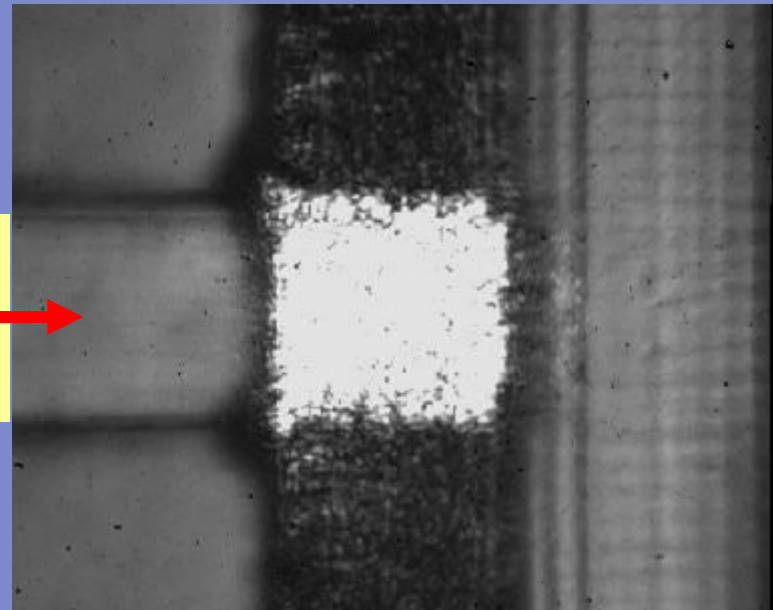
Waveguide terminated with 45-deg mirror

Out-of-plane coupling,
using 45-deg mirror (silver)



Microscope image looking
down on mirror
coupling light towards camera

OPTICAL INPUT



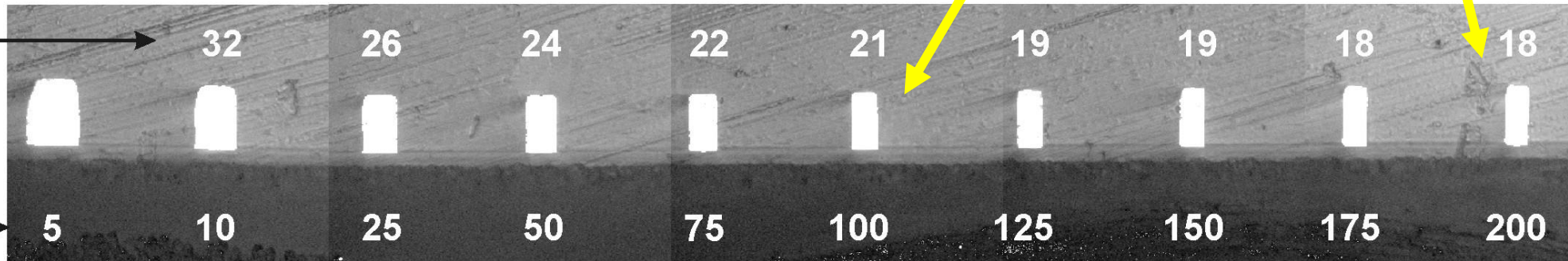
Results with a Gaussian spot profile (2)

Laser-writing Parameters:

- Profile: **Gaussian**, 1 mm $1/e^2$ TEM₀₀ beam with 40 mm EFL lens
- Optical power available: ~9 mW
- Cores written in air
- Variable writing speed

Approximate height of waveguide cores: 45 - 50 μm

Approximate width (μm)



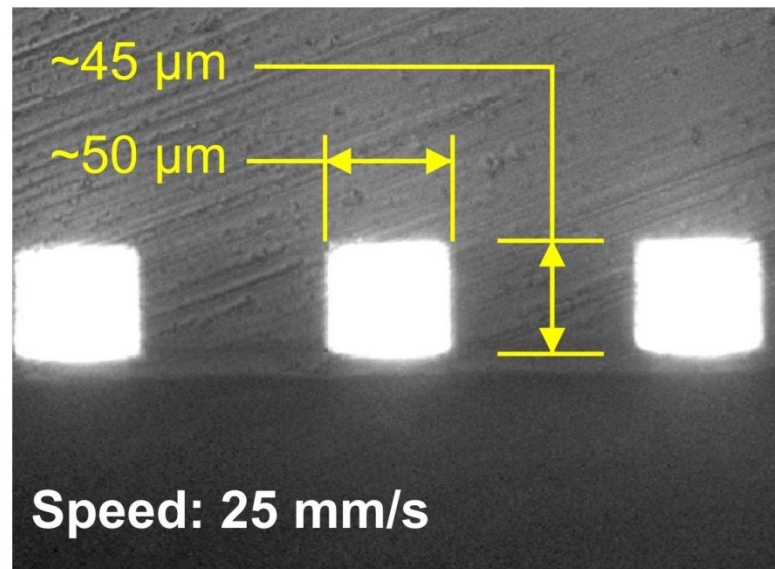
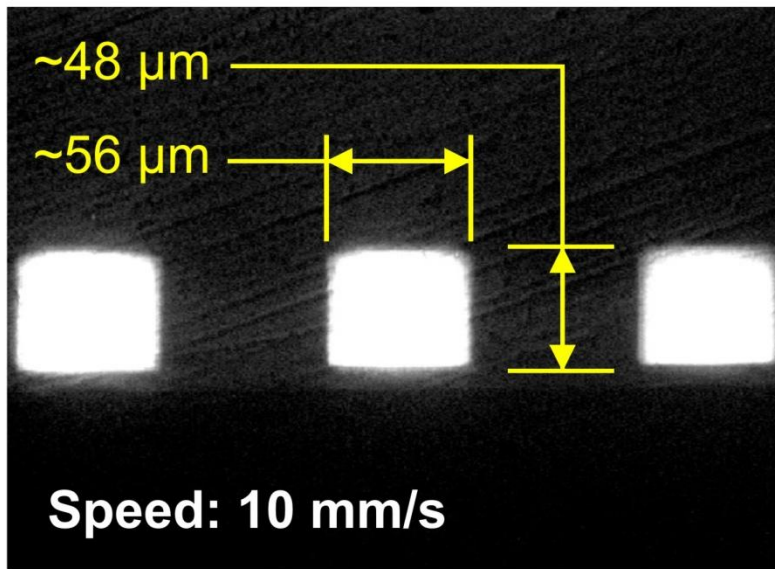
Writing speed (mm/s)

(Waveguide cores on a 125 μm pitch)

Results with an imaged circular aperture

Laser-writing Parameters:

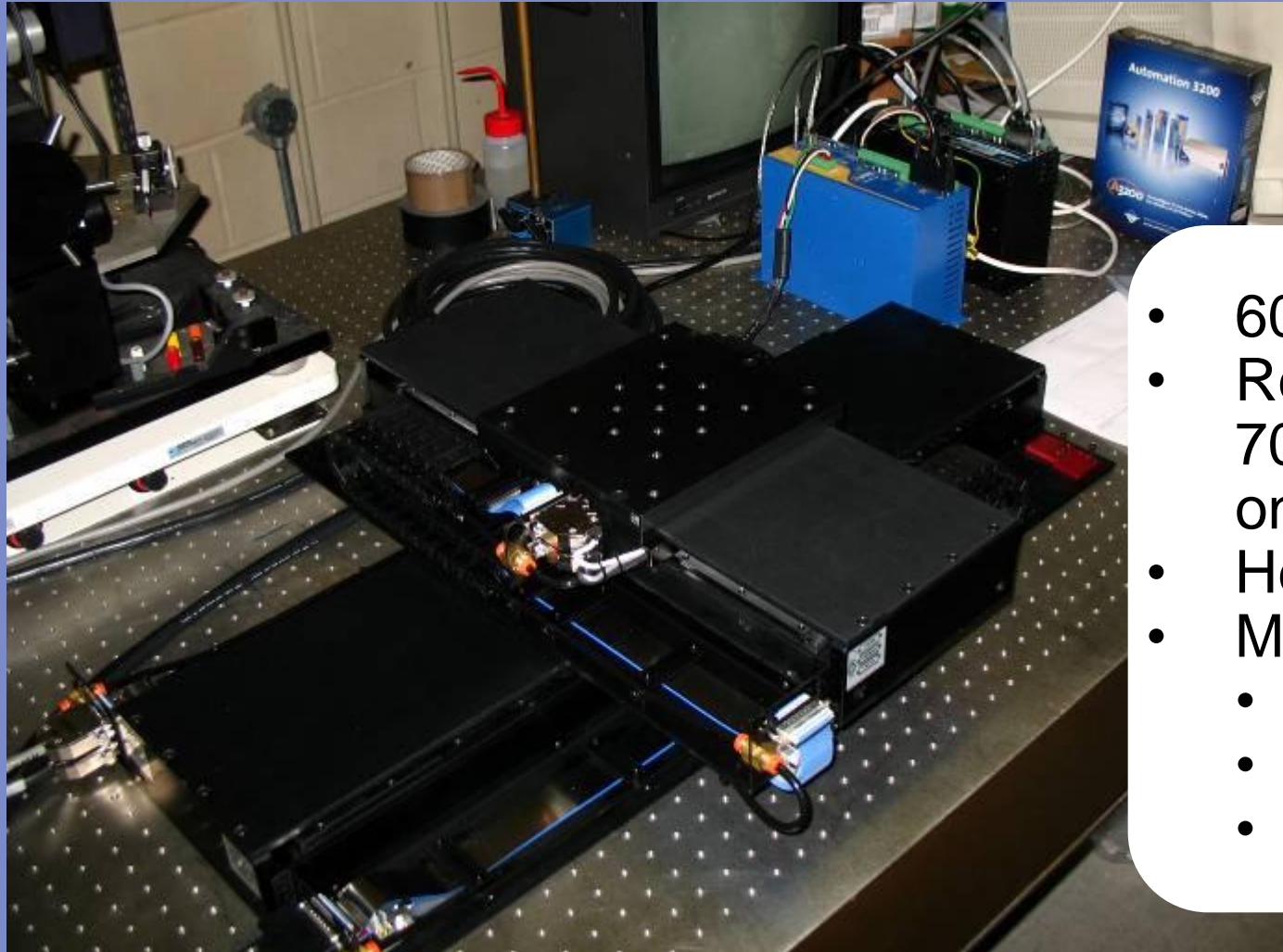
- Profile: **imaged aperture**, 100 μm diameter, illuminated by Gaussian truncated at $\sim 50\%$ peak, 0.5 magnification onto writing plane
- Optical power available for writing: ~ 2 mW
- Cores written in air, on a 125 μm pitch



End-on view of back-illuminated guides

Large Board Processing: Writing

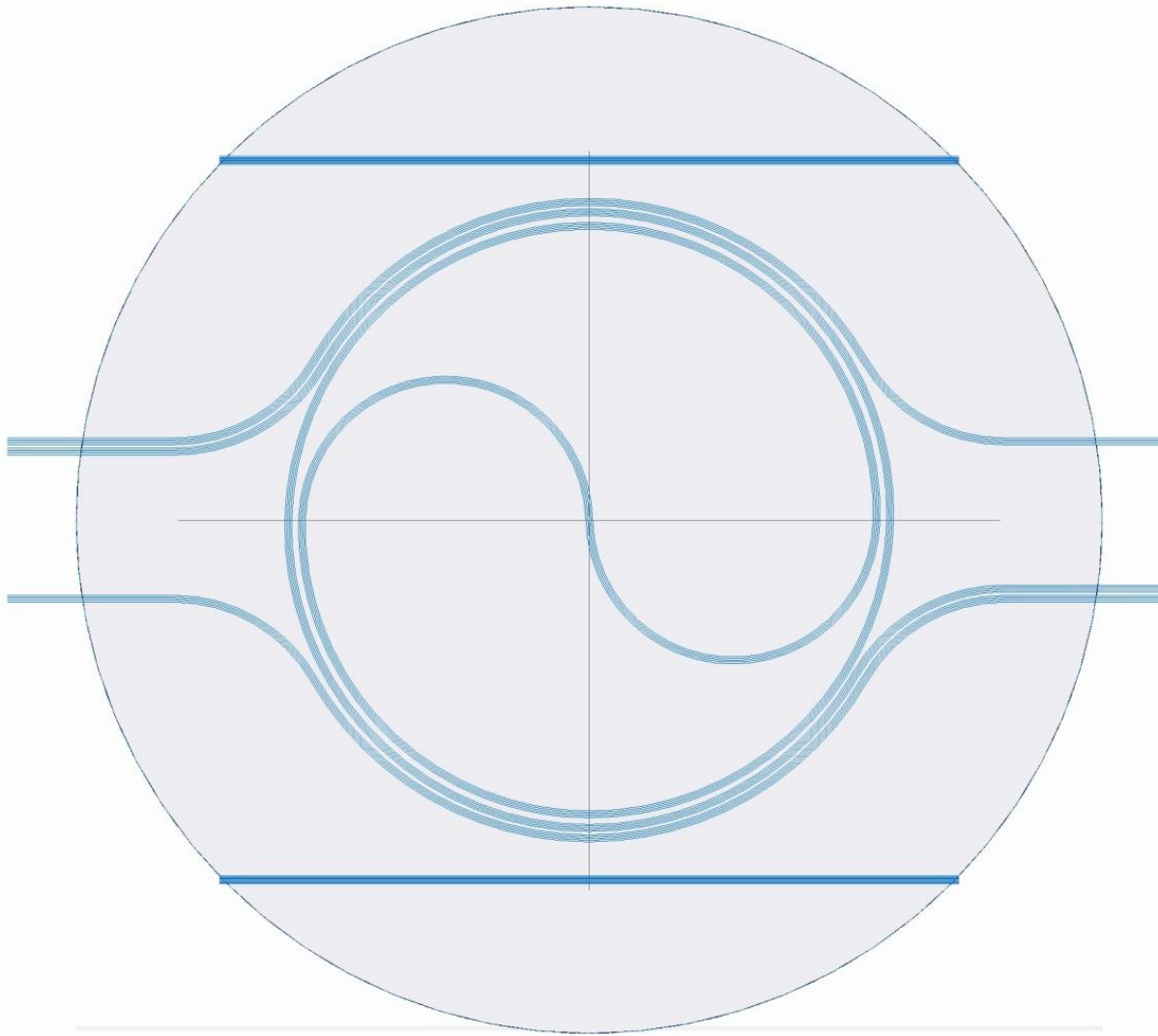
- Stationary “writing head” with board moved using Aerotech sub- μ m precision stages
- Waveguide trajectories produced using CAD program



- 600 x 300 mm travel
- Requires a minimum of 700 x 1000 mm space on optical bench
- Height: ~250 mm
- Mass:
 - 300 mm: 21 kg
 - 600 mm: 33 kg
 - Vacuum tabletop



Test Structures



Spirals:

x5, 250 μm pitch
700 mm long

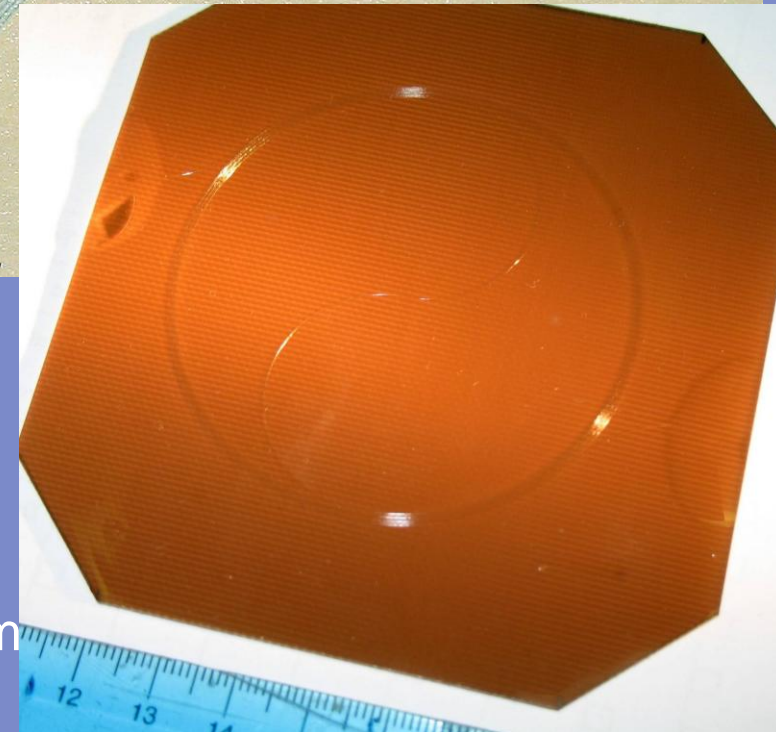
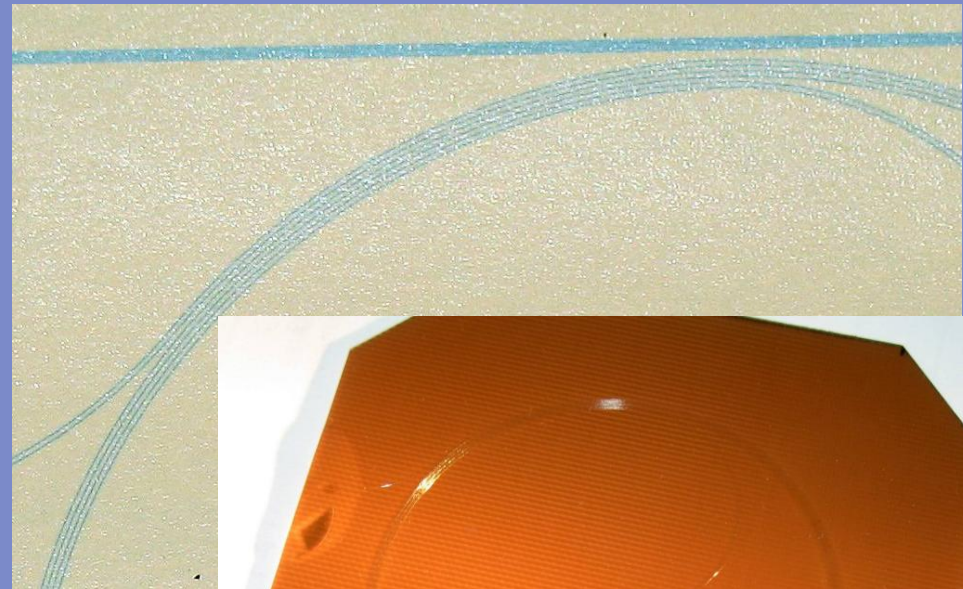
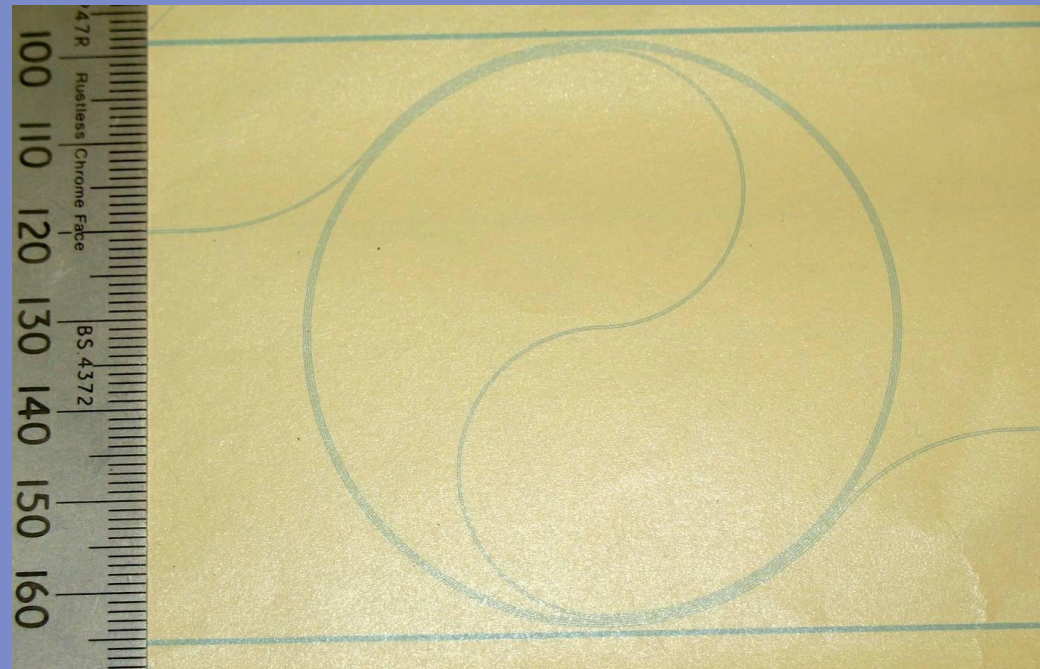
Curves:

x10, 250 μm pitch
170 mm long

Straights:

x20, 125 μm pitch
100 mm long

Large area writing: Spiral Test Structure

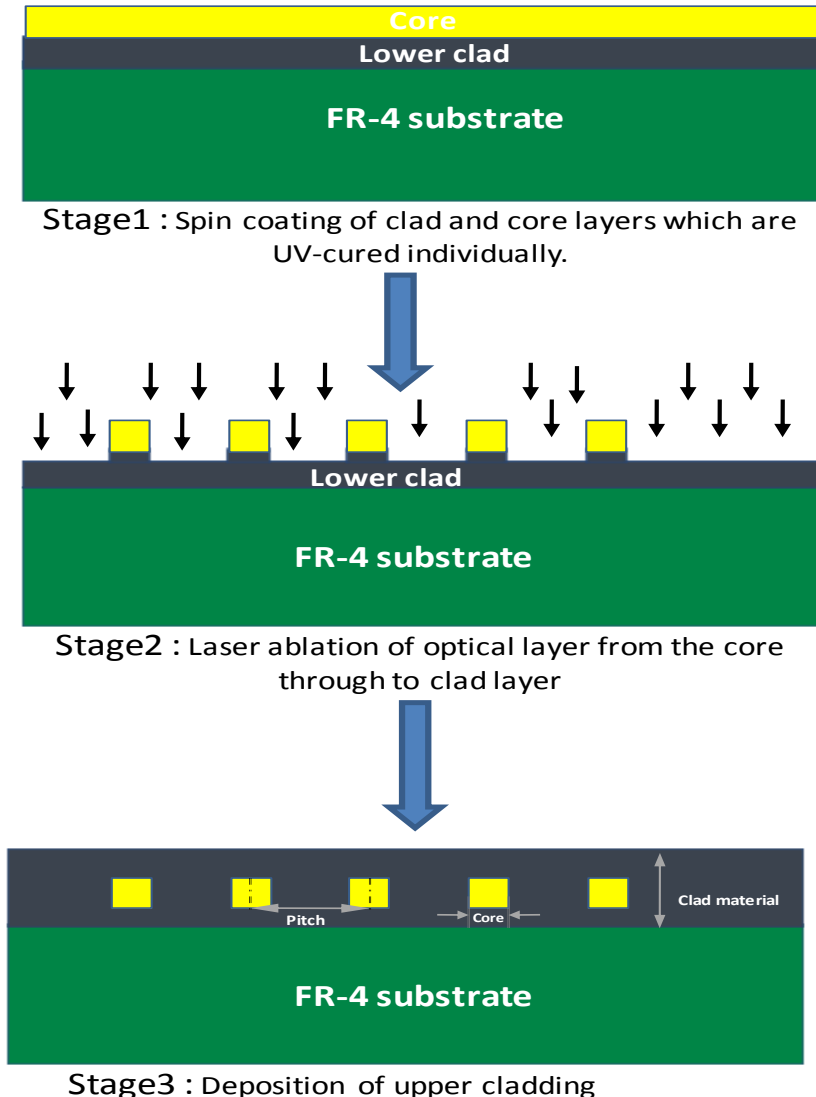


- The guides shown include two parallel spirals plus a number of “straight through” waveguides
- Each spiral has a total path length of ~650 mm
- Minimum bend radius is 16 mm (input/output regions & spiral reversal). Large radius is ~ 32 mm
- Spiral cores are on a 250 μm pitch, straight waveguides are on a 125 μm pitch

Laser Ablation of Optical Waveguides

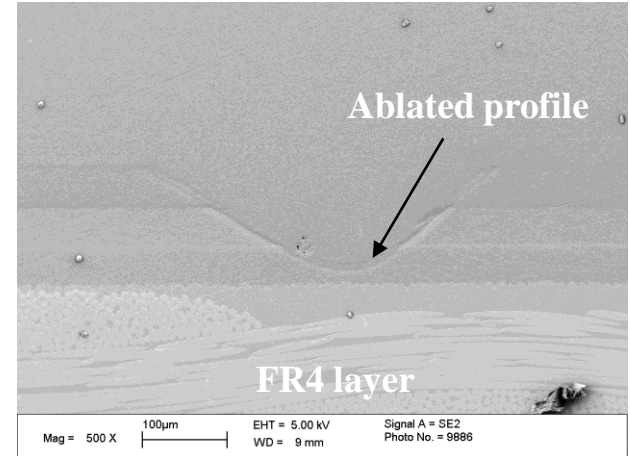
- Research
 - Straight waveguides
 - 2D & 3D integrated mirrors
- Approach
 - Excimer laser – Loughborough
 - CO₂ laser - Loughborough
 - UV Nd:YAG – Stevenage Circuits Ltd
- Optical polymer
 - Truemode® – Exxelis
 - Polysiloxane – Dow Corning

Schematic diagram (side view) showing stages in the fabrication of optical waveguides by laser ablation

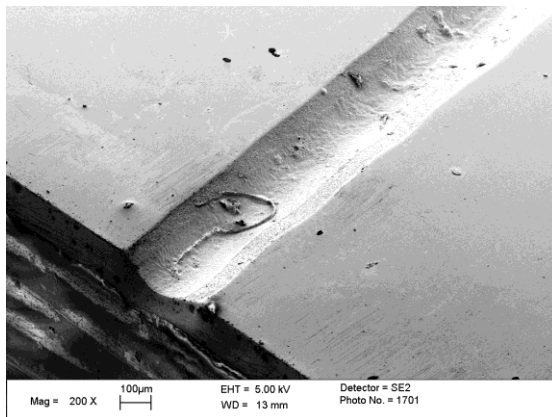


Machining of Optical Polymer with CO₂ Laser

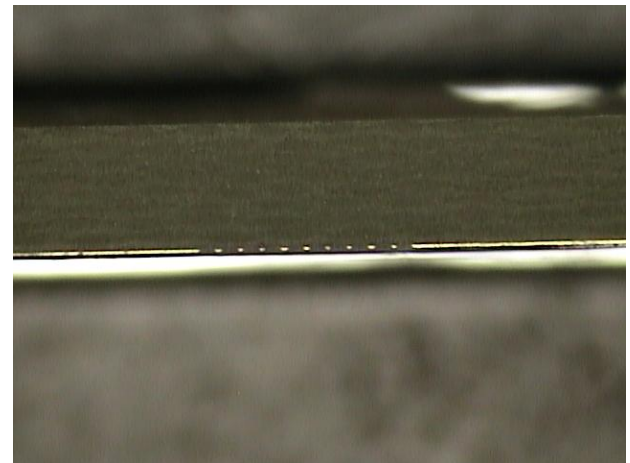
- System
 - 10 Watt(max.) power CW beam
 - Wavelength = 10.6 μm (infrared)
- Process
 - Thermally-dominated ablation process
- Machining quality
 - Curved profile
 - Waveguide fabrication underway



Side view of machined trench

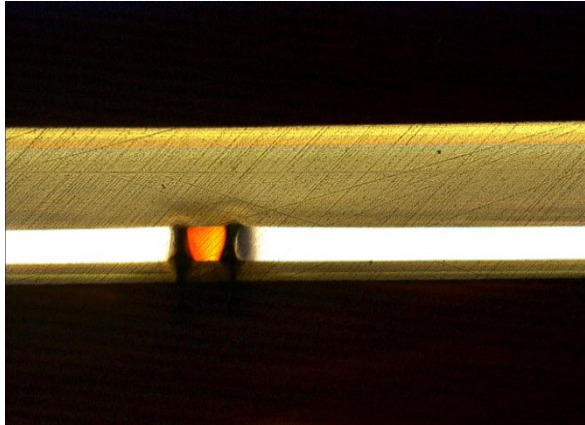


Machined trench

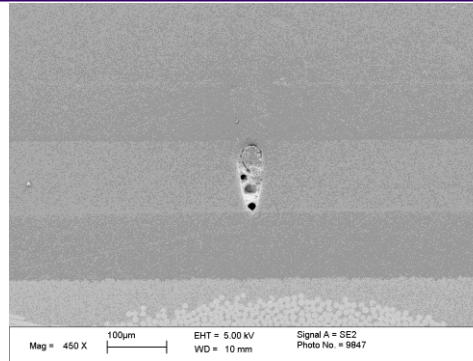
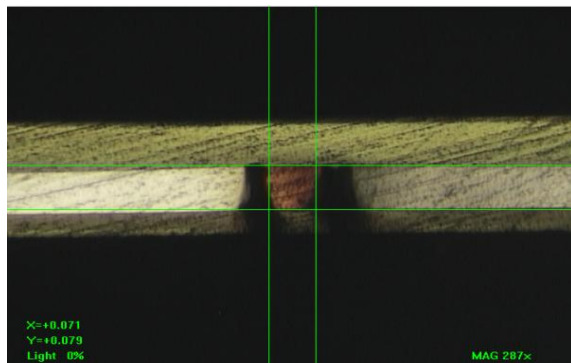


Waveguides (side view)

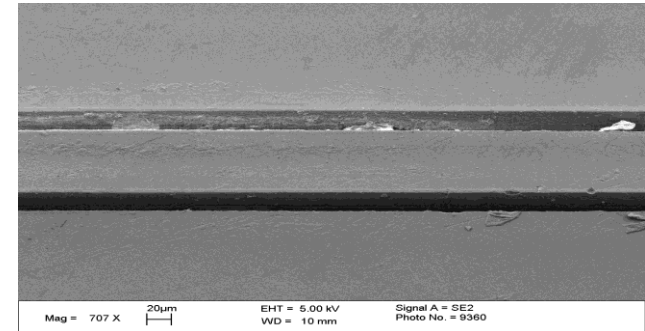
UV Nd:YAG machining in collaboration with Stevenage Circuits Ltd



- Waveguide of $71\text{ }\mu\text{m}$ x $79\text{ }\mu\text{m}$ fabricated using UV Nd:YAG
- Waveguide detected using back lighting



Side view



Plan view

System

- 355 nm (UV) Pulsed laser with 60 ns pulse width and Gaussian beam (TEM_{00}) or “Tophat” profile at Stevenage Circuits Ltd.

Process

- Photochemically-dominated ablation process.

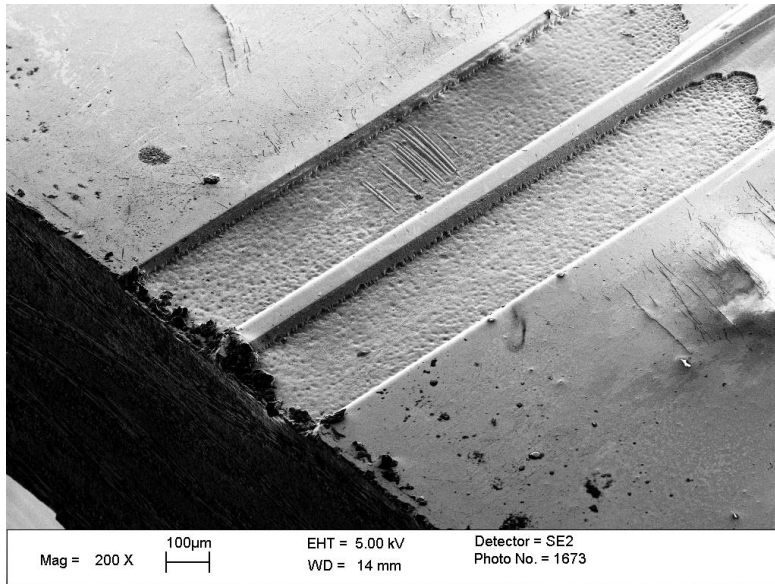


Waveguide quality

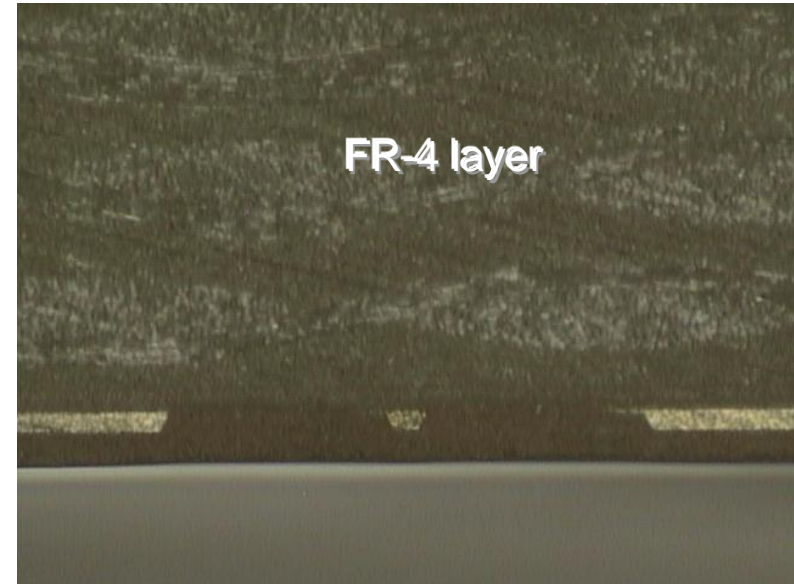
- Minimum Heat Affected Zone
- Propagation loss measurement underway

Machining of Optical Polymer with Excimer Laser

- Straight structures machined in an optical polymer.
- Future work to investigate preparation of mirrors for in and out of plane bends.

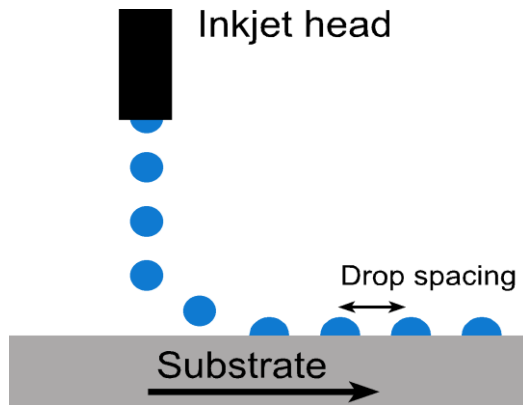


Machined trenches

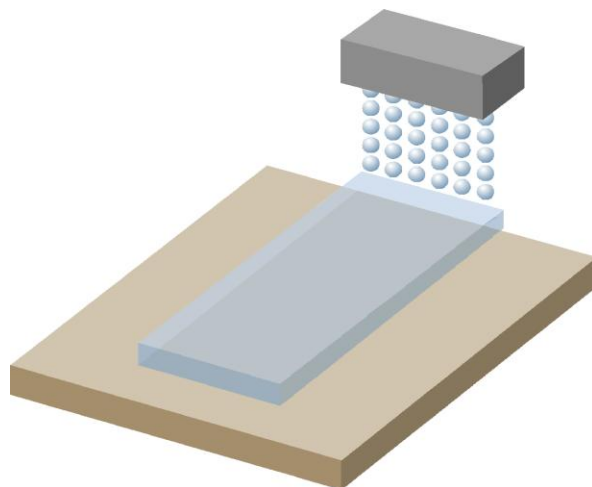


Waveguide structure

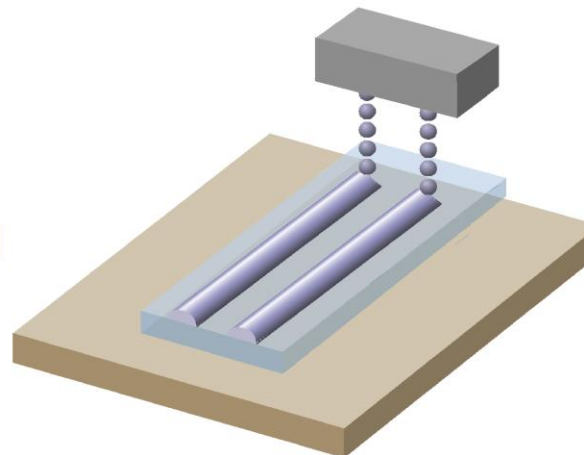
Inkjetting as a Route to Waveguide Deposition



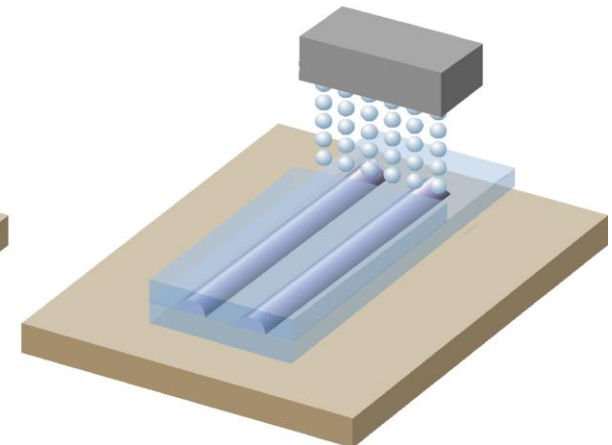
- Print polymer then UV cure
- Advantages:
 - controlled, selective deposition of core and clad
 - less wastage: picolitre volumes
 - large area printing
 - low cost



**Deposit
Lower Cladding**



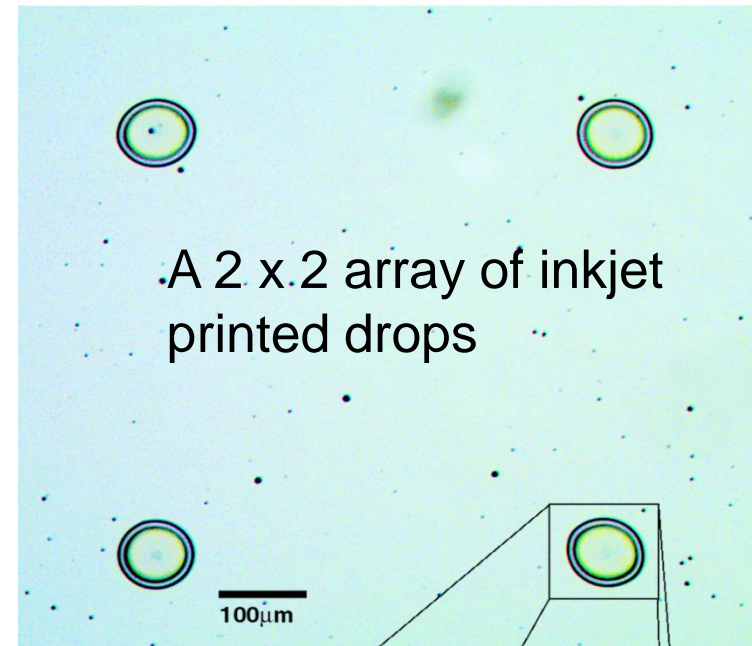
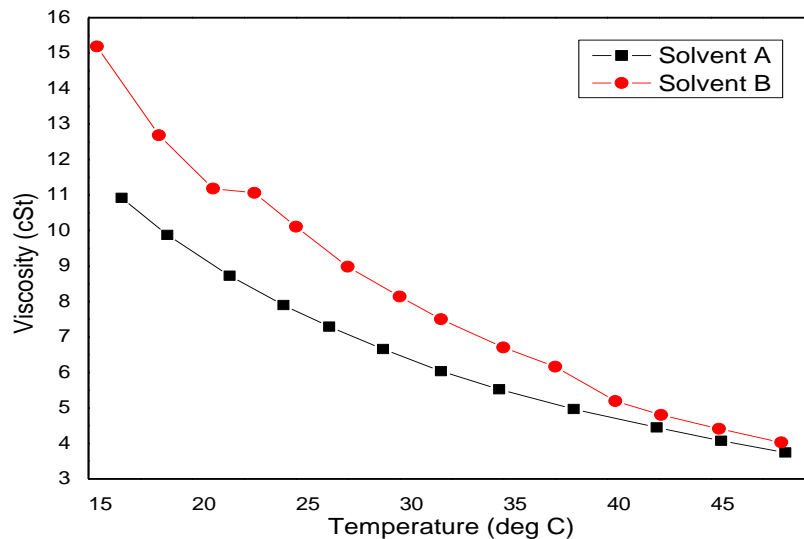
**Deposit
Core**



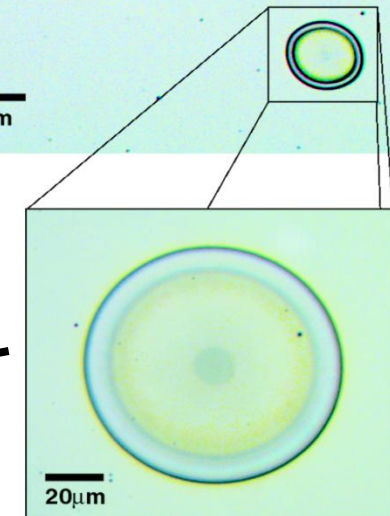
**Deposit
Upper Cladding**

Challenges of Inkjet Deposition

- Viscosity tailored to inkjet head via addition of solvent
- “Coffee stain” effects

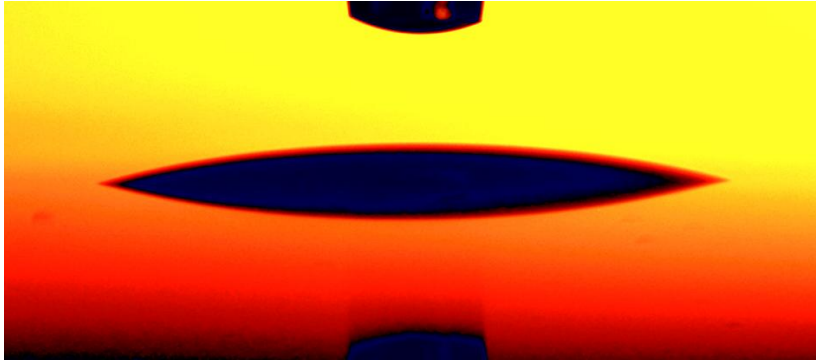


Cross-section of dried droplet
“coffee-stain” effect

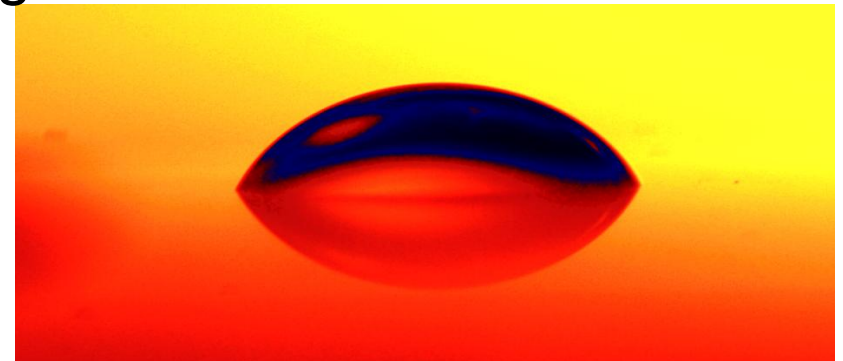


Changing Surface Wettability

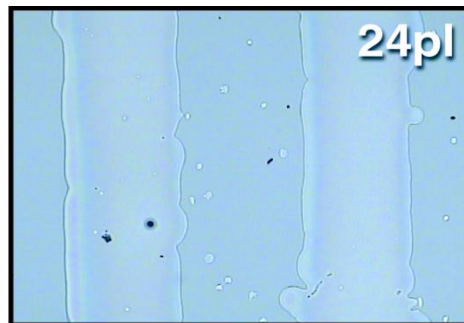
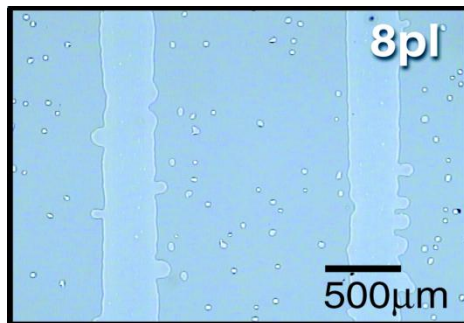
Contact Angles



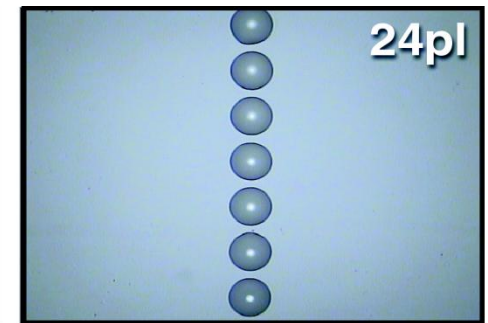
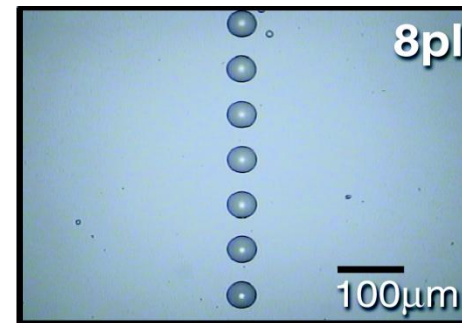
Core material on cladding



Core material on modified glass surface (hydrophobic)



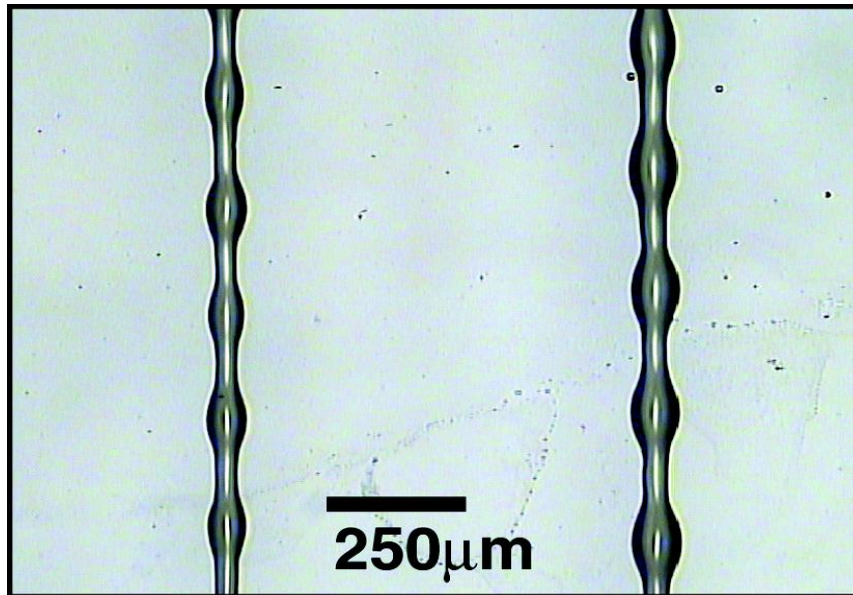
Large wetting - broad inkjetted lines



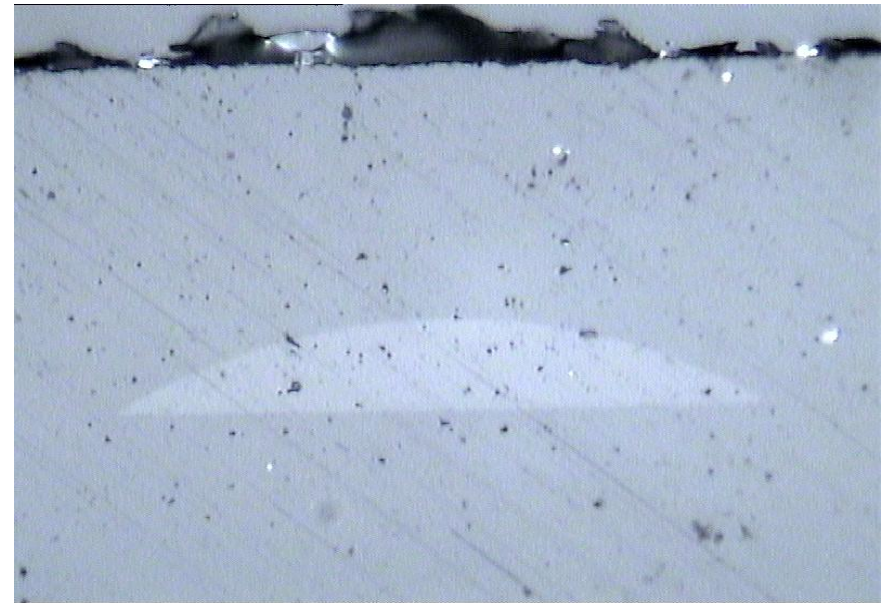
Reduced wetting – discrete droplets

Identical inkjetting conditions - spreading inhibited on modified surface

Towards Stable Structures



Stable line structures with periodic features

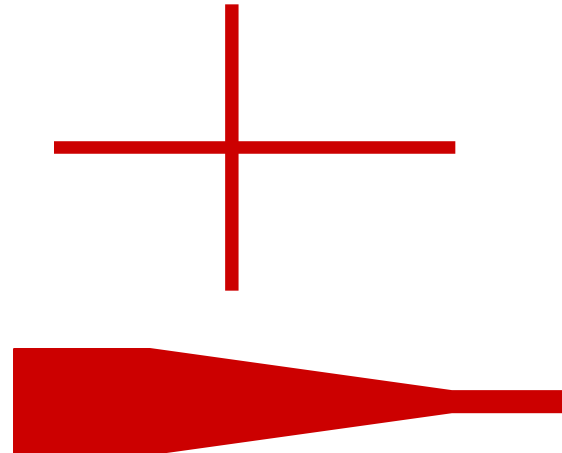


Cross section of inkjetted core material surrounded by cladding (width 80 microns)

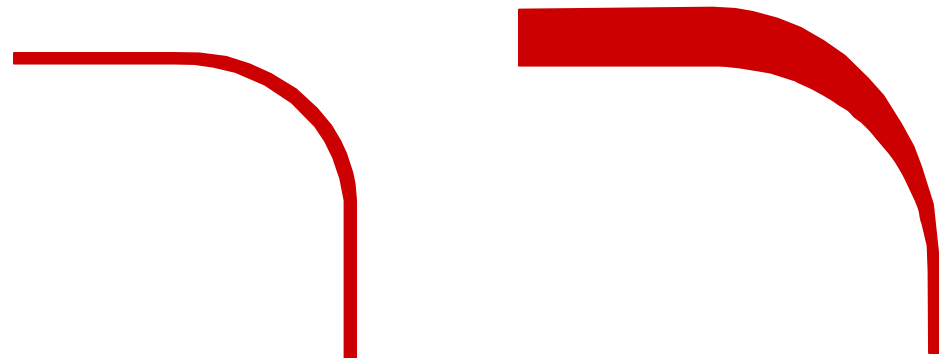
A balance between wettability, line stability and adhesion

Waveguide components and measurements

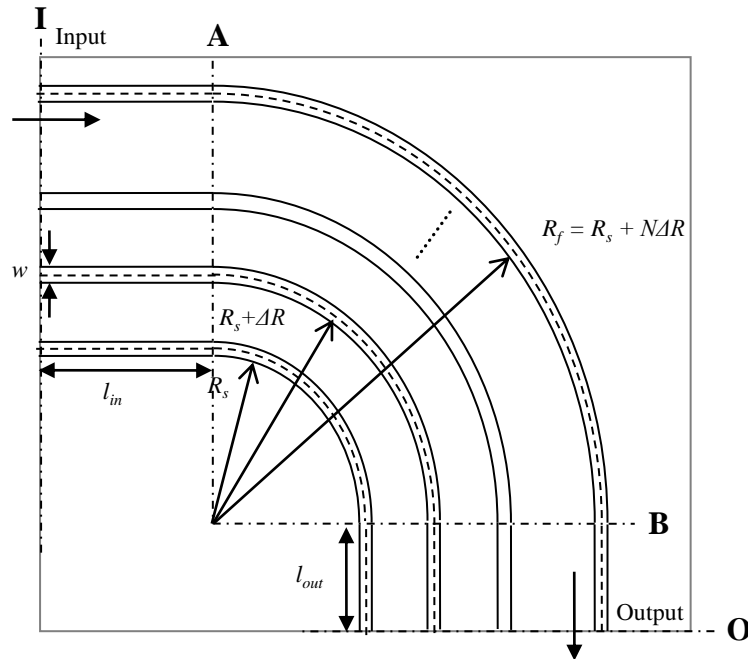
- Straight waveguides 480 mm x 70 μm x 70 μm
- Bends with a range of radii
- Crossings
- Spiral waveguides
- Tapered waveguides
- Bent tapered waveguides



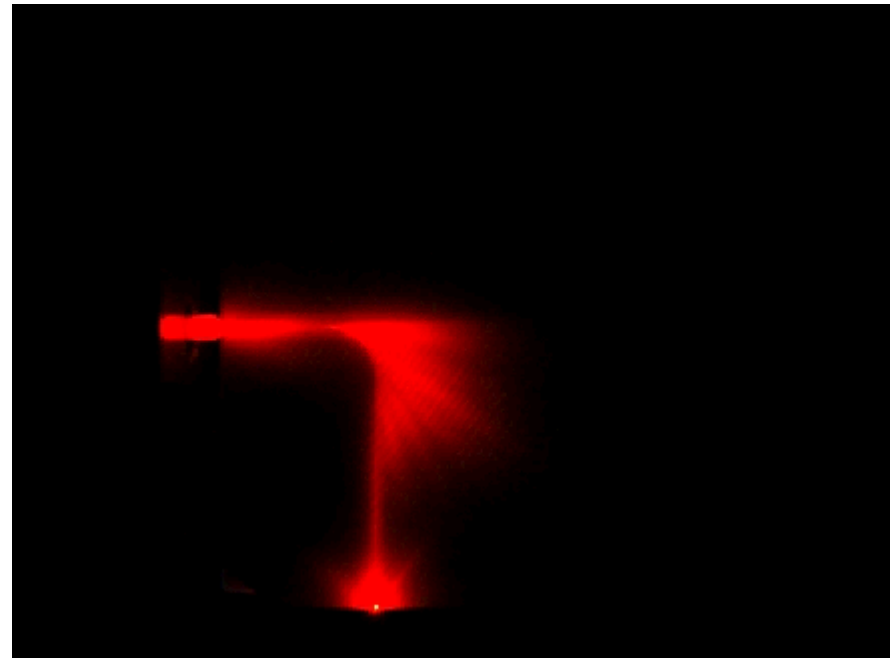
- Loss
- Crosstalk
- Misalignment tolerance
- Surface Roughness
- Bit Error Rate, Eye Diagram



Optical Power Loss in 90° Waveguide Bends



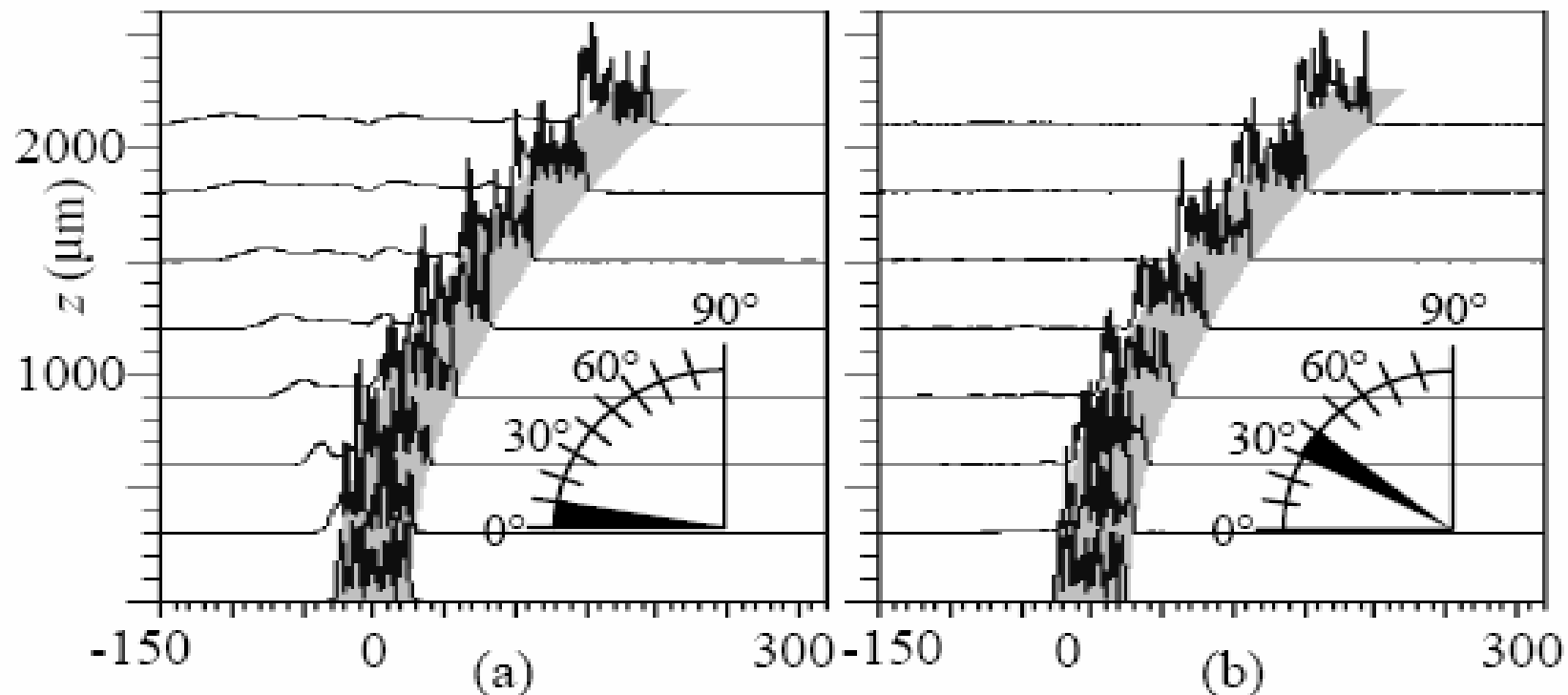
Schematic diagram of one set of curved waveguides.



Light through a bent waveguide of $R = 5.5 \text{ mm} - 34.5 \text{ mm}$

- Radius R , varied between $5.5 \text{ mm} < R < 35 \text{ mm}$, $\Delta R = 1 \text{ mm}$
- Light lost due to scattering, transition loss, bend loss, reflection and back-scattering
- Illuminated by a MM fiber with a red-laser.

BPM, beam propagation method modeling of optical field in bend segments

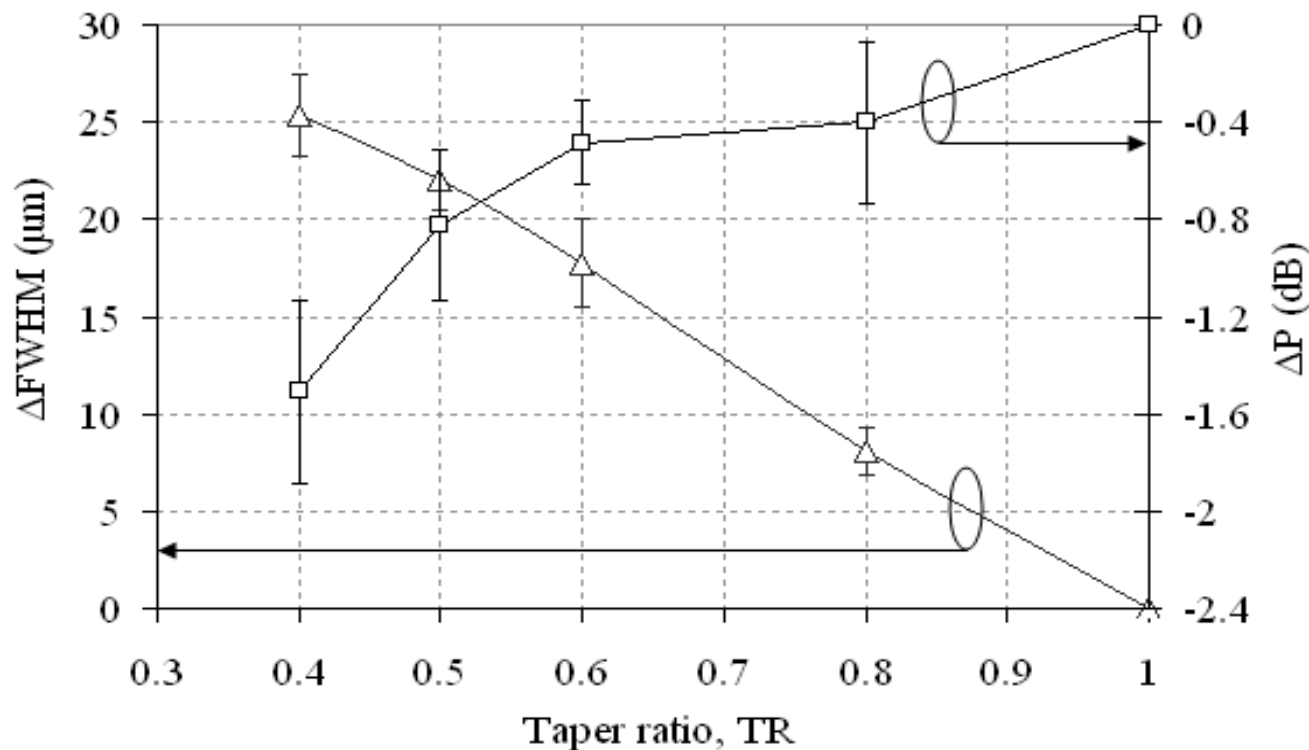


$w = 50 \mu\text{m}$, $R = 13 \text{ mm}$

(left picture) in the first segment (first 10°).

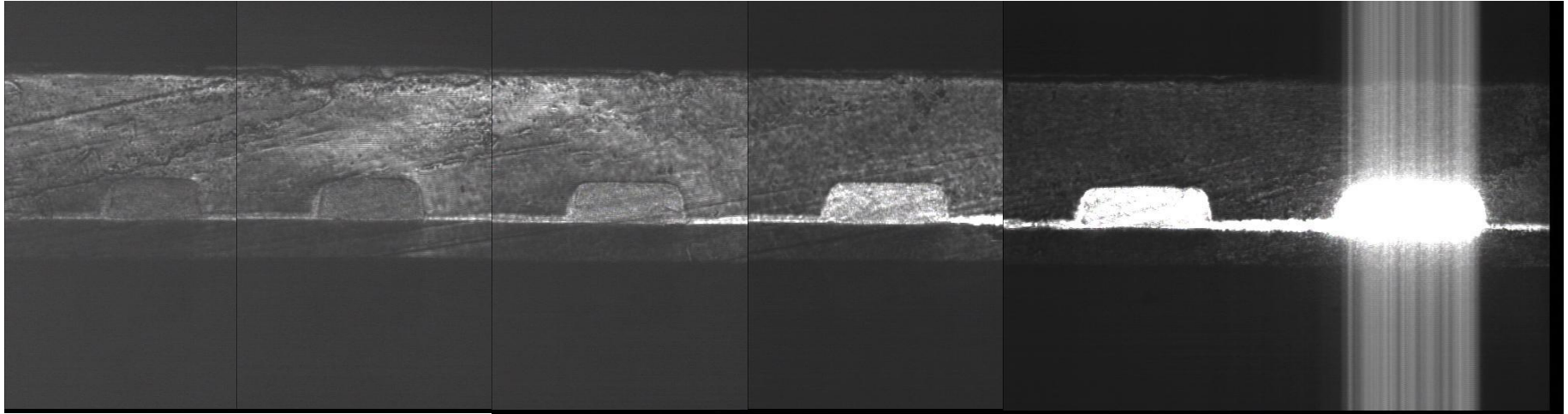
(right picture) in the 30° to 40° degree segment.

Differences in misalignment tolerance and loss as a function of taper ratio



- Graph plots the differences between a tapered bend and a bend
- There is a trade off between insertion loss and misalignment tolerance

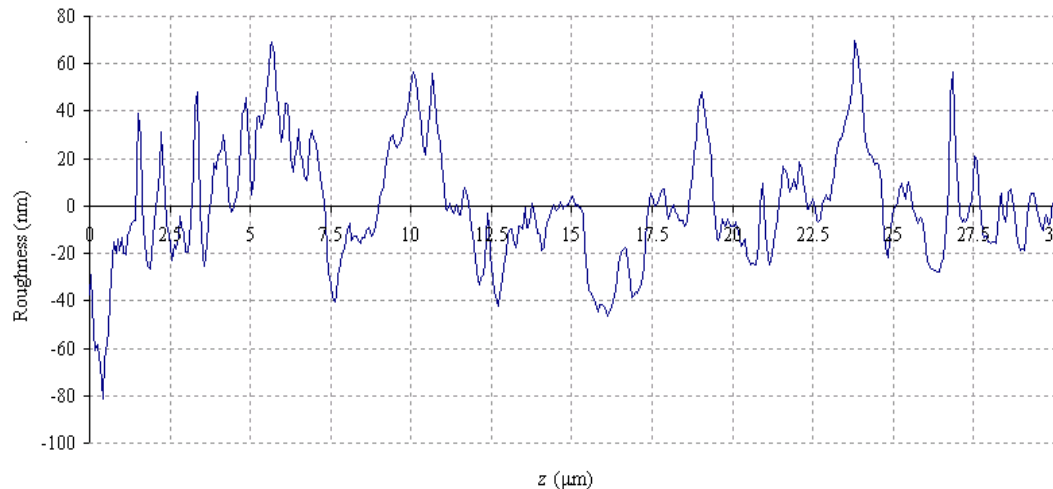
Crosstalk in Chirped Width Waveguide Array



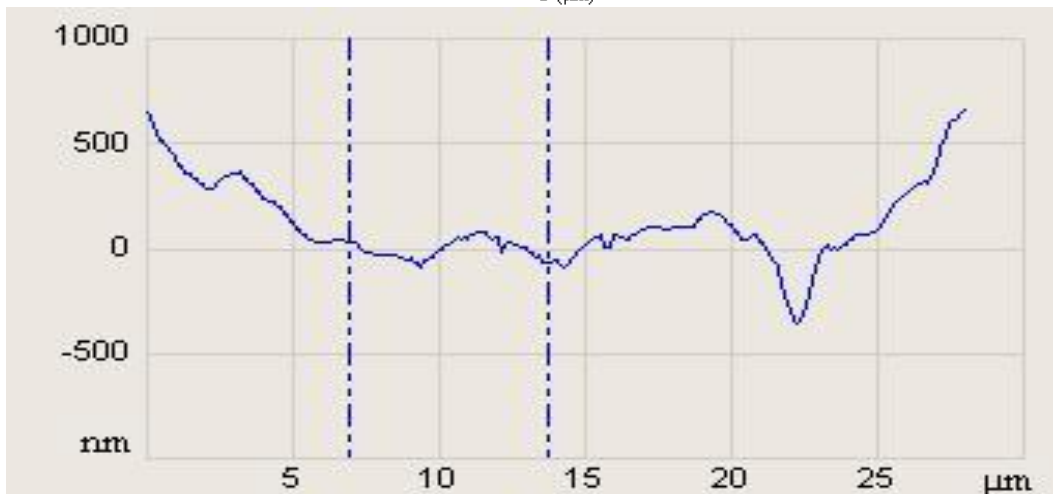
100 μm 110 μm 120 μm 130 μm 140 μm 150 μm

- Light launched from VCSEL imaged via a GRIN lens into 50 μm x 150 μm waveguide
- Photolithographically fabricated chirped with waveguide array
- Photomosaic with increased camera gain towards left

Surface roughness

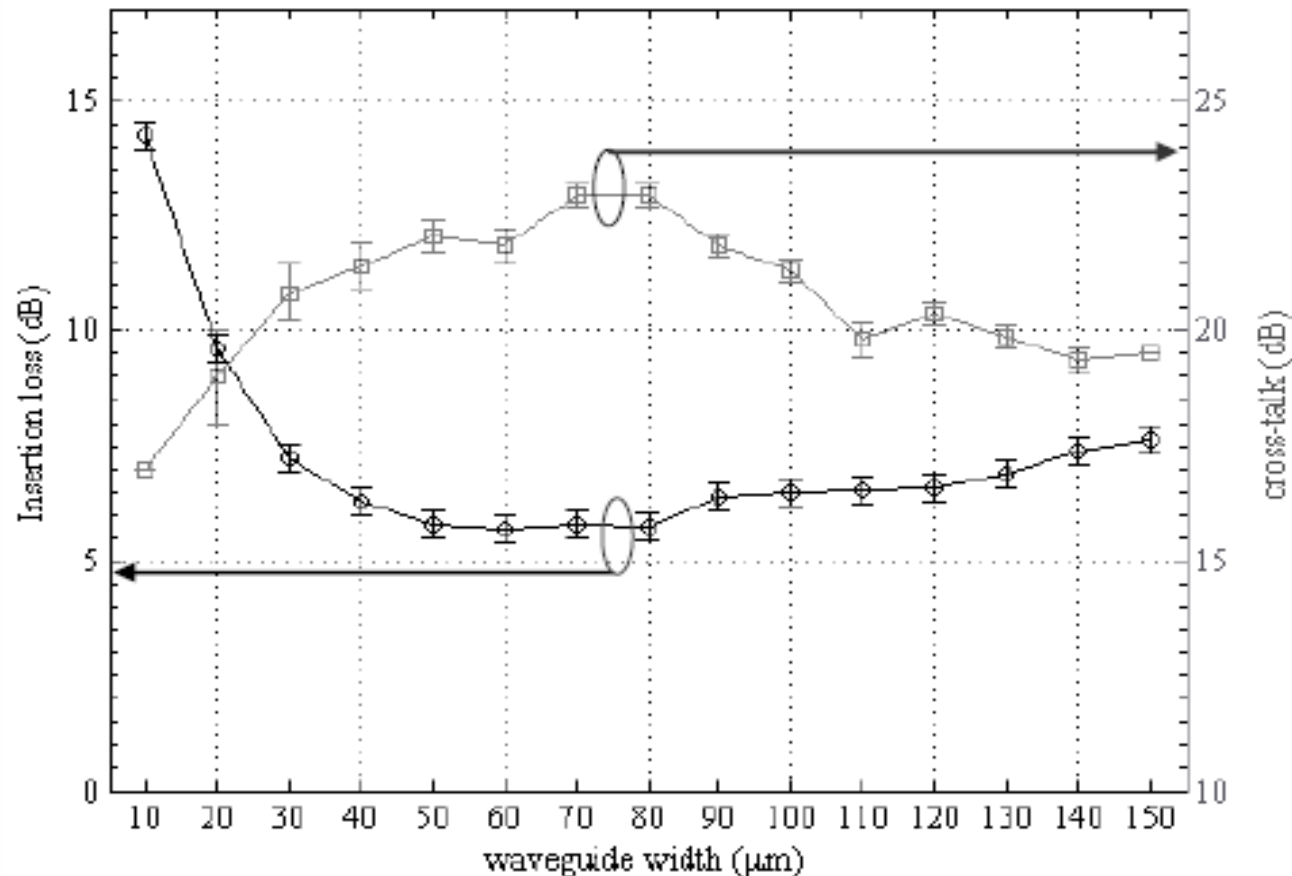


- RMS side wall roughness: 9 nm to 74 nm



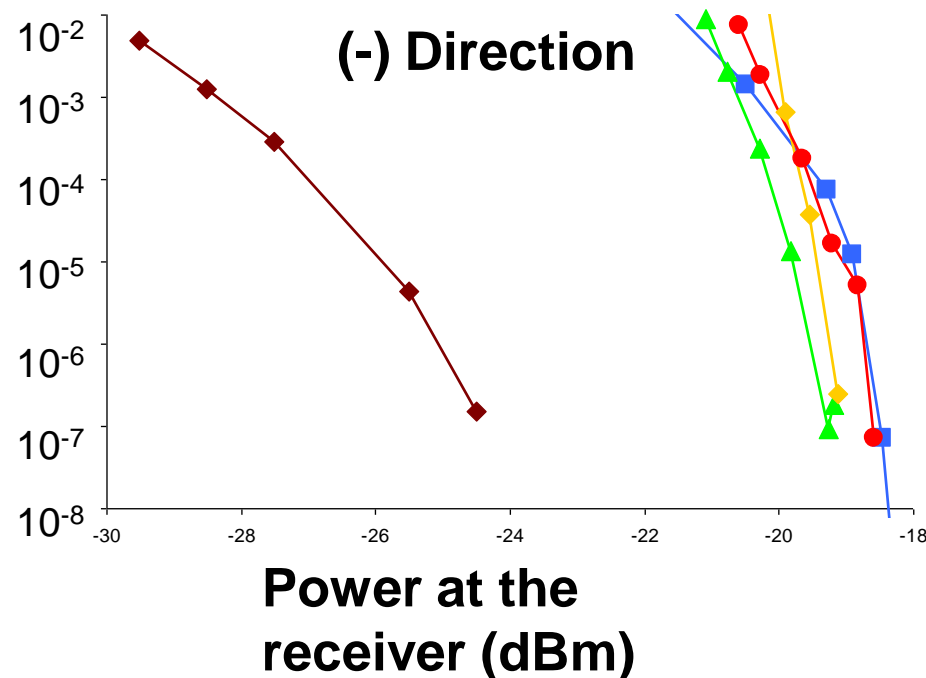
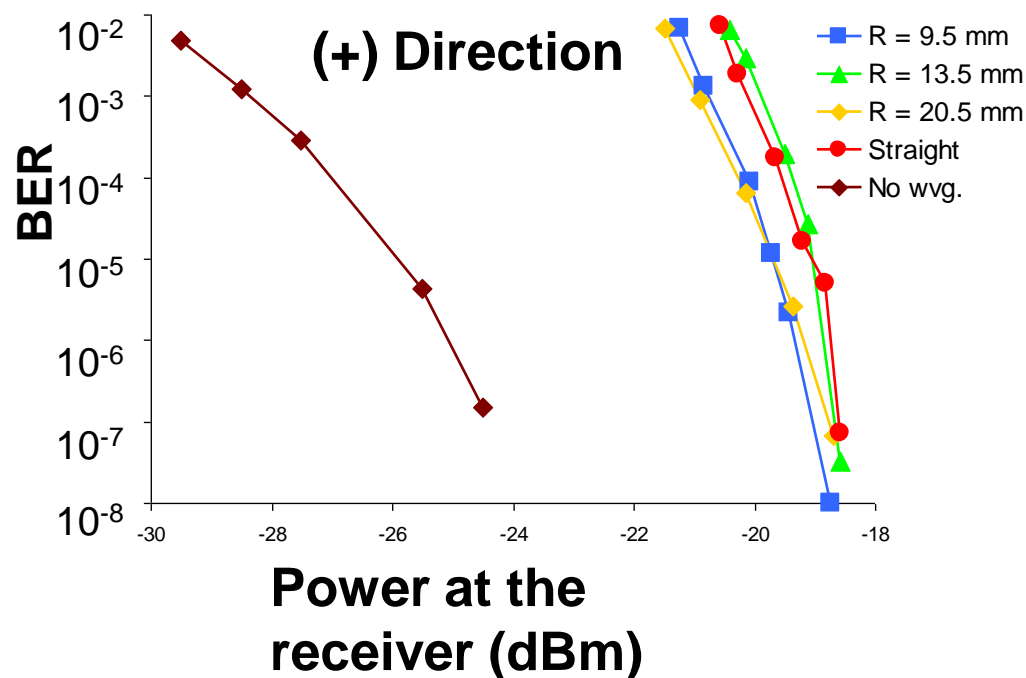
- RMS polished end surface roughness: 26 nm to 192 nm.

Design rules for waveguide width depending on insertion loss and cross-talk

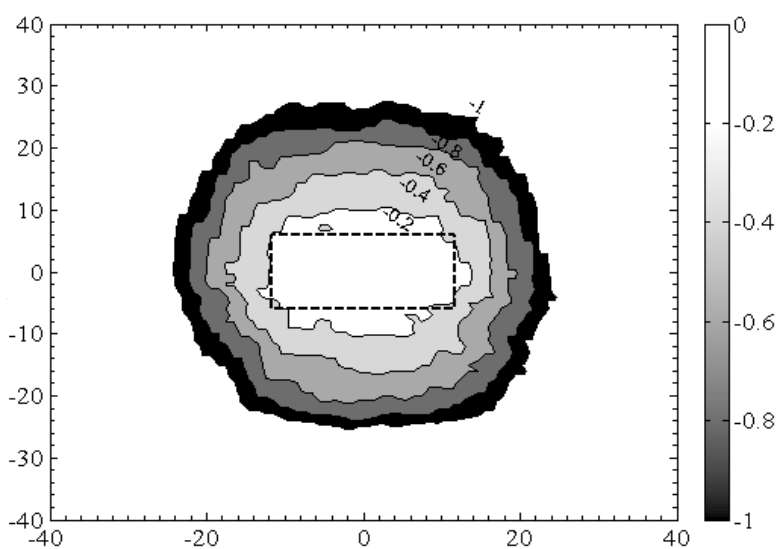


6~7dB for a 70 μm width waveguide

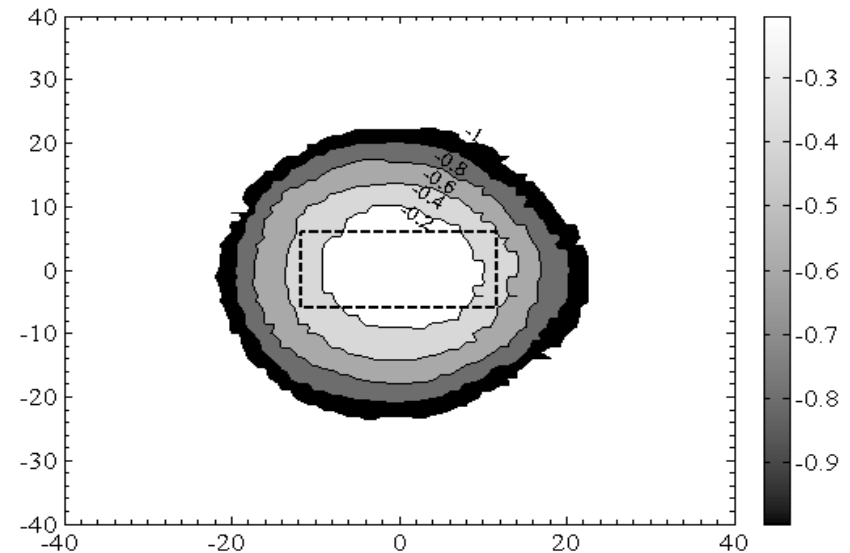
Bit error rate for laterally misaligned 1550 nm 2.5 Gb/s DFB laser



Contour map of VCSEL and PD misalignment



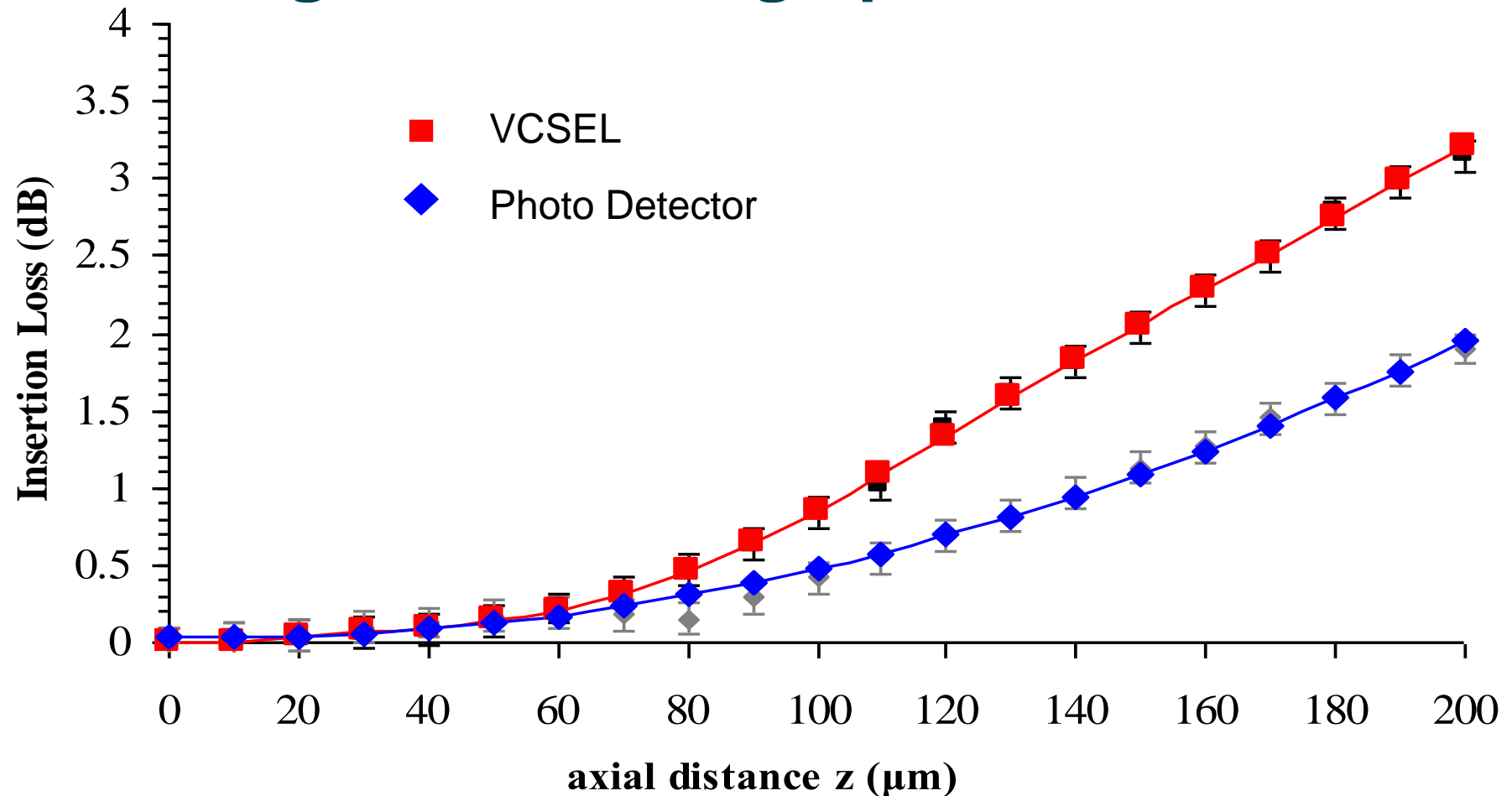
(a) Contour map of relative insertion loss compared to the maximum coupling position for VCSEL misalignment at $z = 0$.



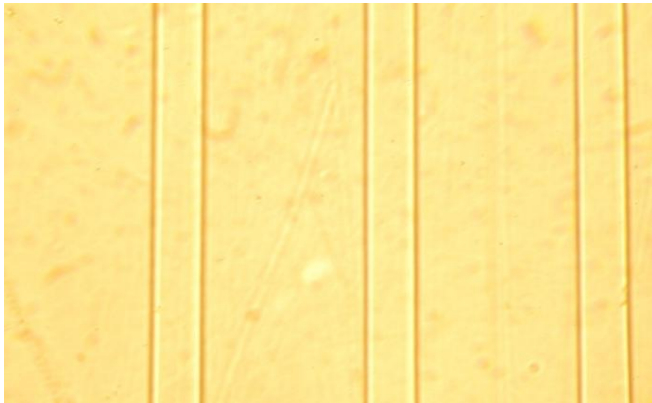
(b) Same for PD misalignment at $z = 0$. Resolution step was $\Delta x = \Delta y = 1 \mu\text{m}$.

- Dashed rectangle is the expected relative insertion loss according to the calculated misalignments along x and y .
- The minimum insertion loss was 4.4 dB, corresponded to $x = 0, y = 0, z = 0$

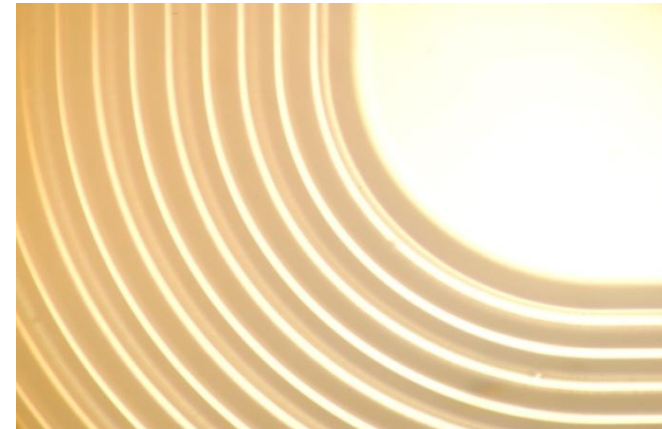
Coupling Loss for VCSEL and PD for misalignments along optic axis



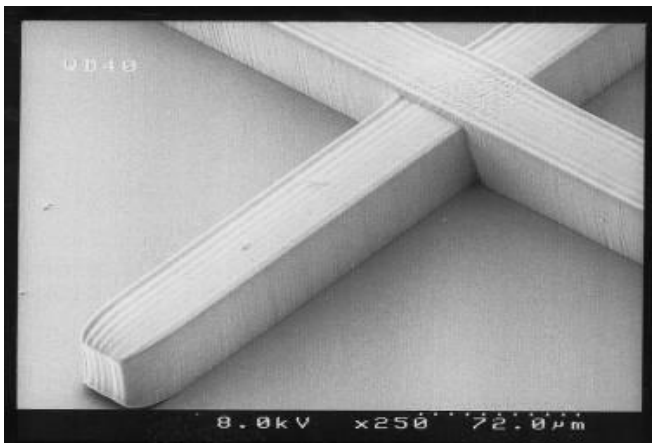
Fabrication Techniques and Waveguides Samples



Straight waveguides – Optical InterLinks



90° Crossings – Dow Corning

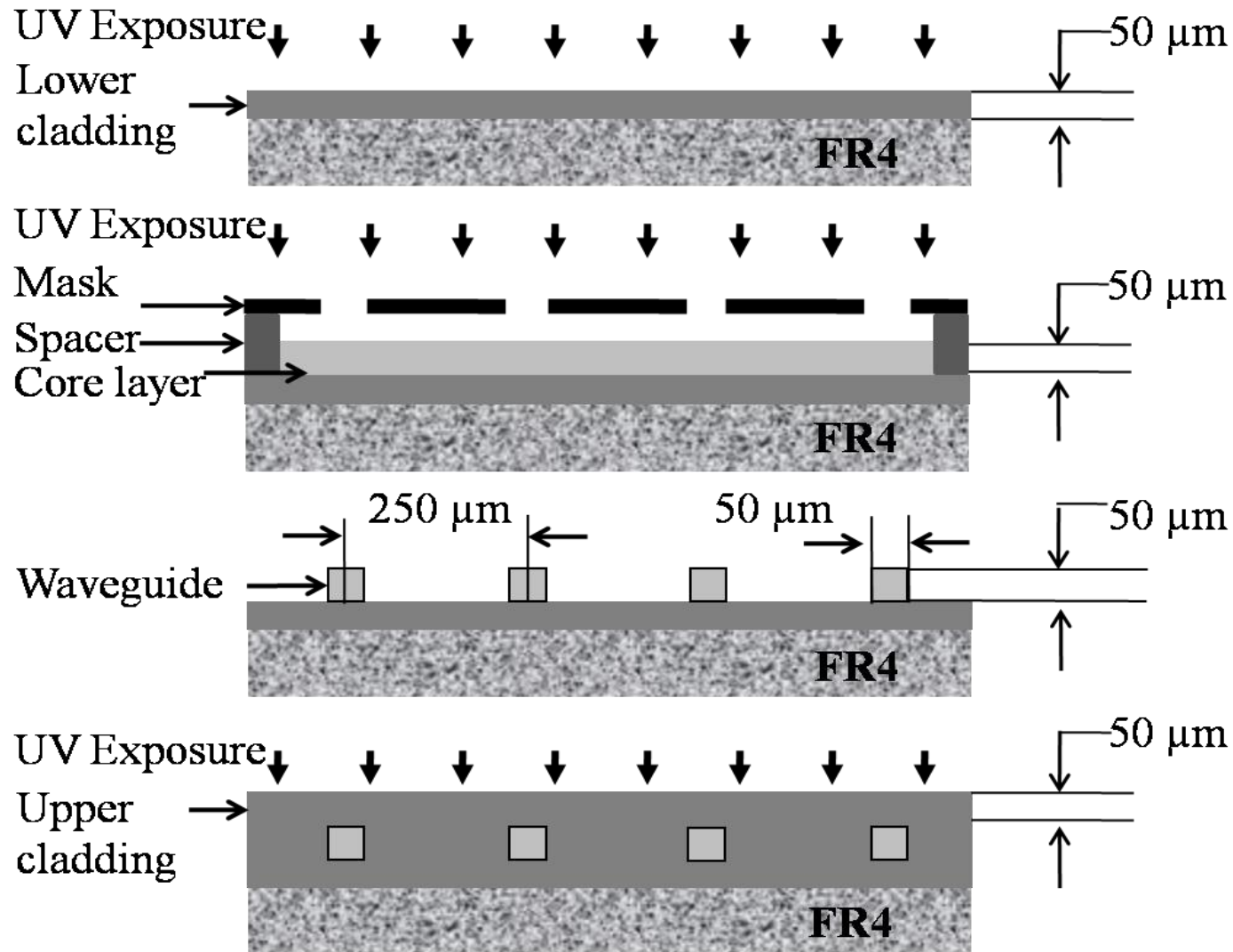


90° Crossings – Heriot Watt University

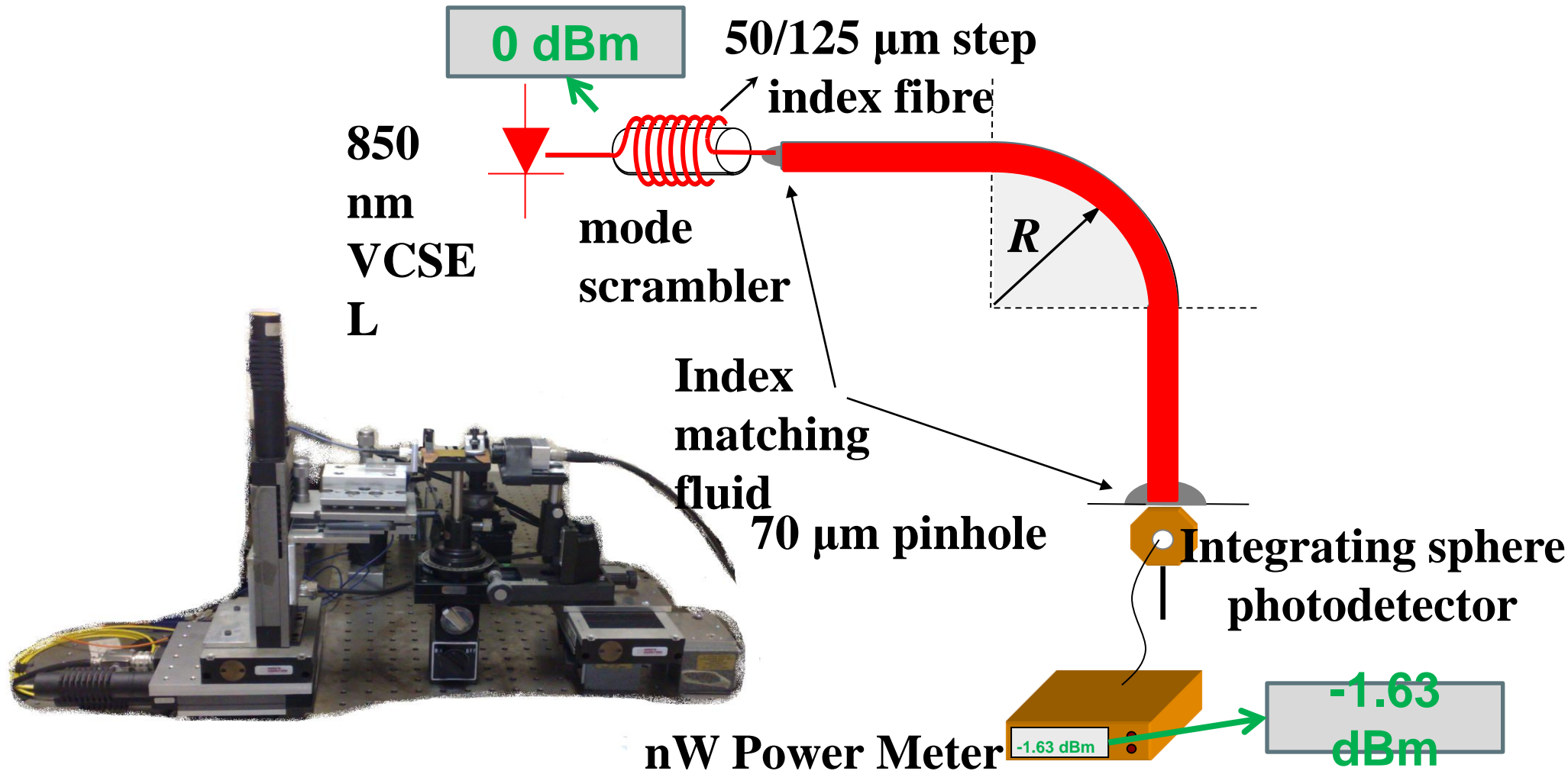


50° Crossings – Exxelis

Photolithographic Fabrication of Waveguides



Optical Loss Measurement



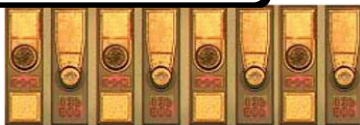
VCSEL Array for Crosstalk Measurement

PIN Array



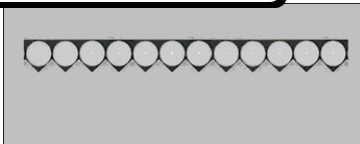
Source: Microsemi Corporation

VCSEL Array

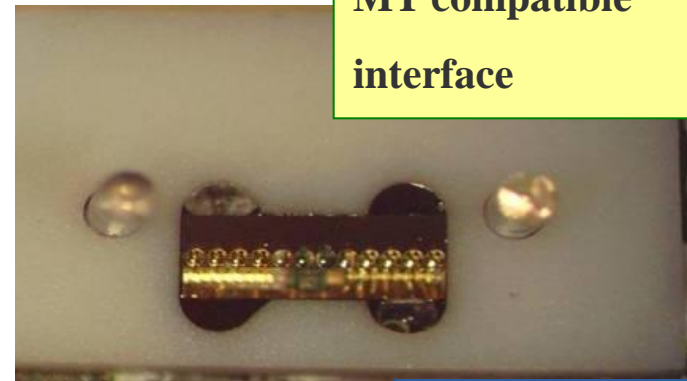
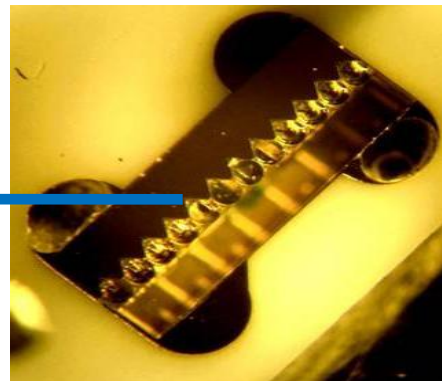


Source: ULM Photonics GmbH

GRIN Lens Array



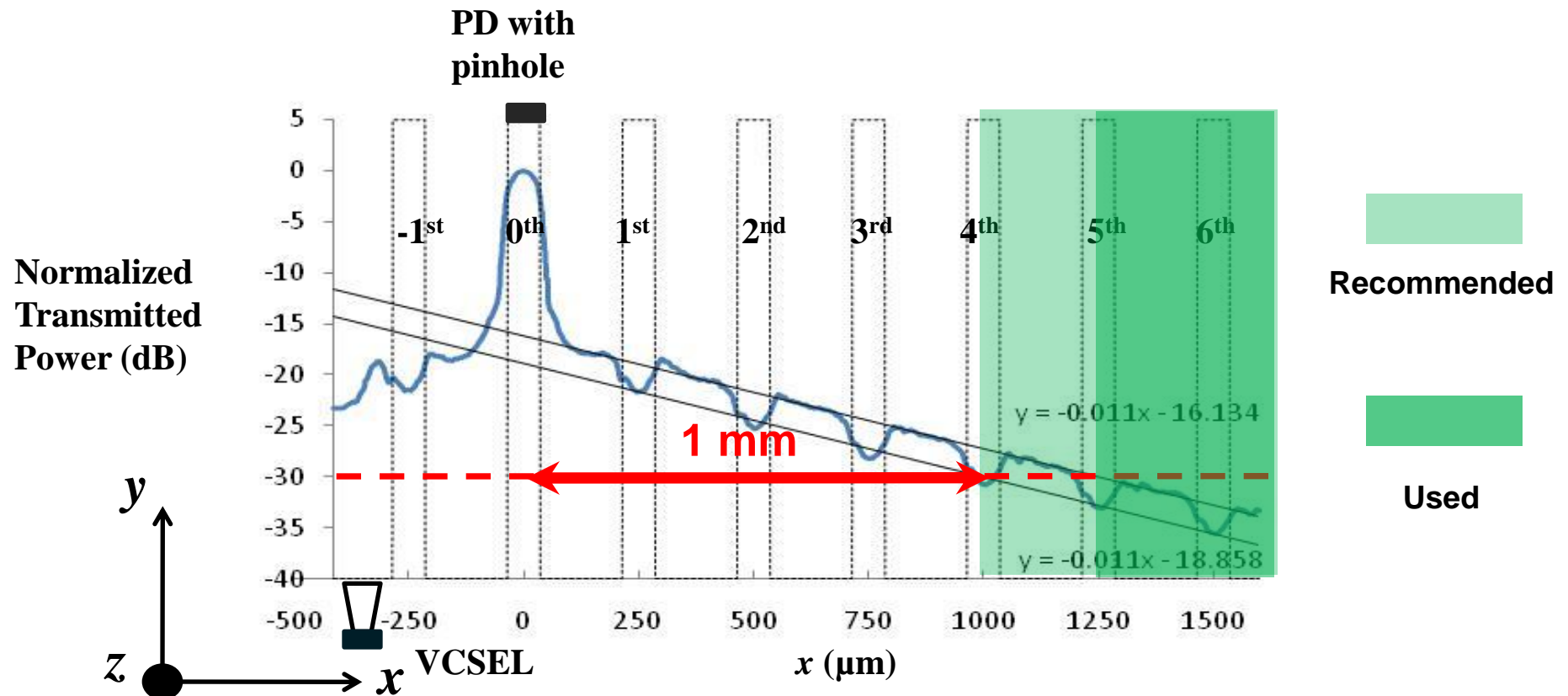
Source: GRINTech GmbH



MT compatible
interface

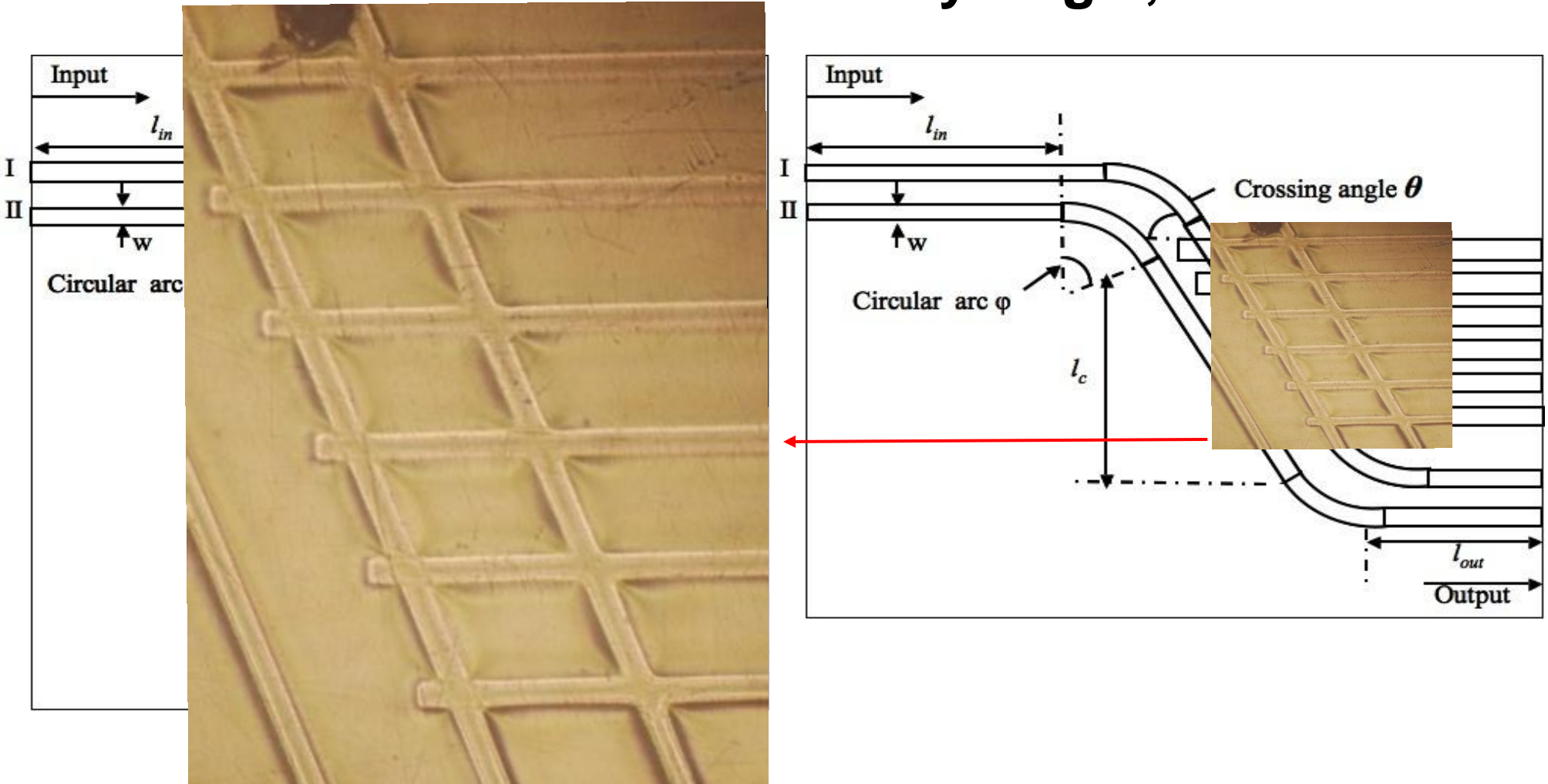
x-y-r-a-t-e-x

Design Rules for Inter-waveguide Cross Talk

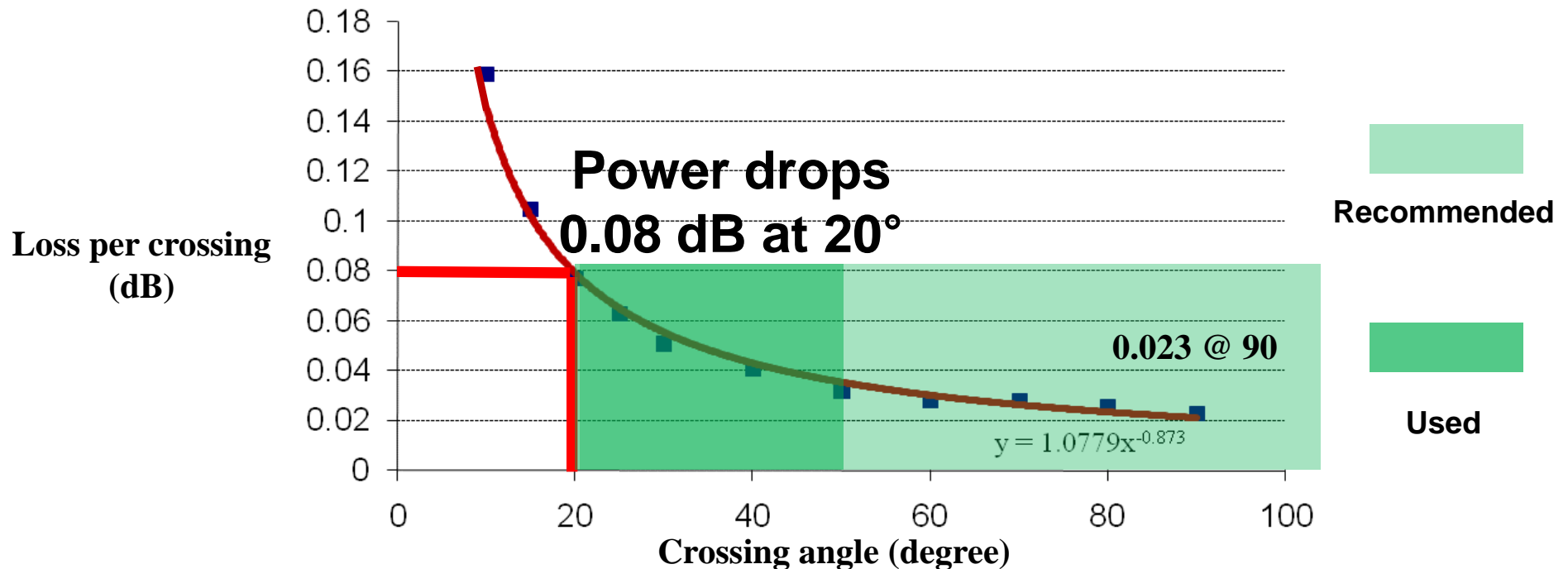


- $70 \mu\text{m} \times 70 \mu\text{m}$ waveguide cross sections and 10 cm long
- In the cladding power drops linearly at a rate of $0.011 \text{ dB}/\mu\text{m}$
- Crosstalk reduced to -30 dB for waveguides 1 mm apart

Schematic Diagram Of Waveguide Crossings at 90° and at an Arbitrary Angle, θ

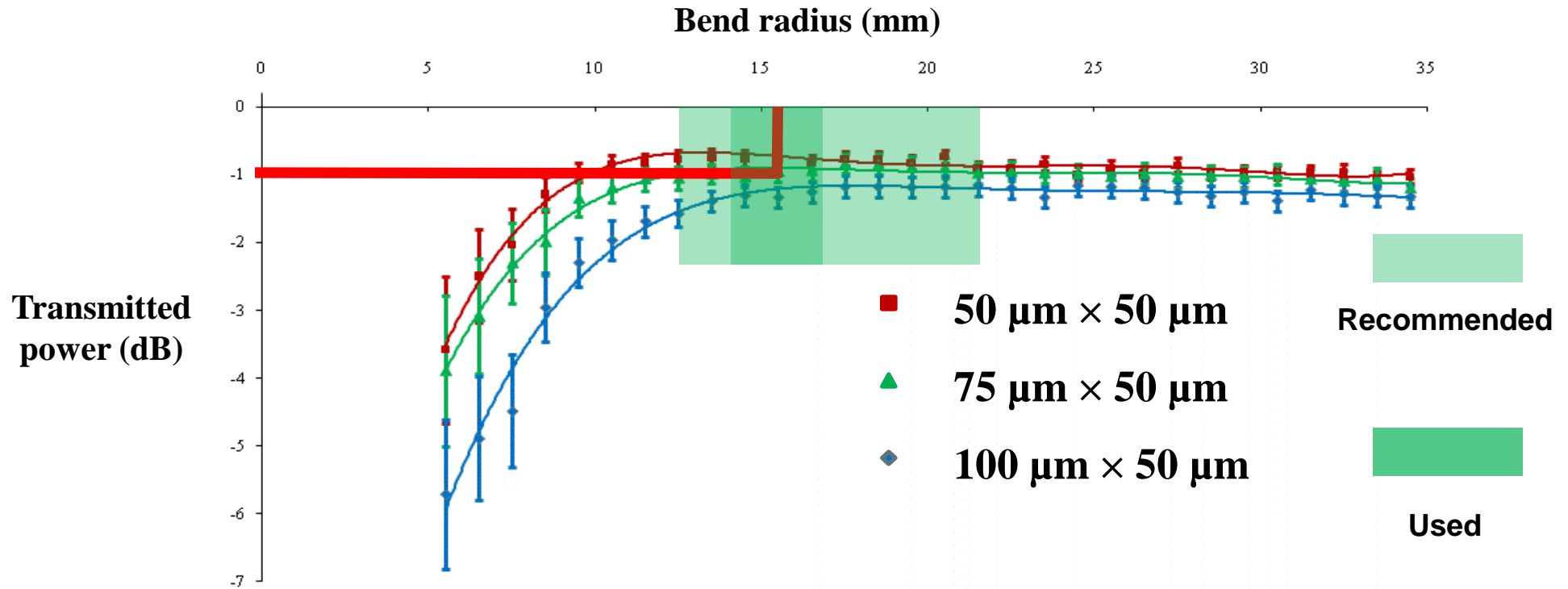


Design Rules for Arbitrary Angle Crossings



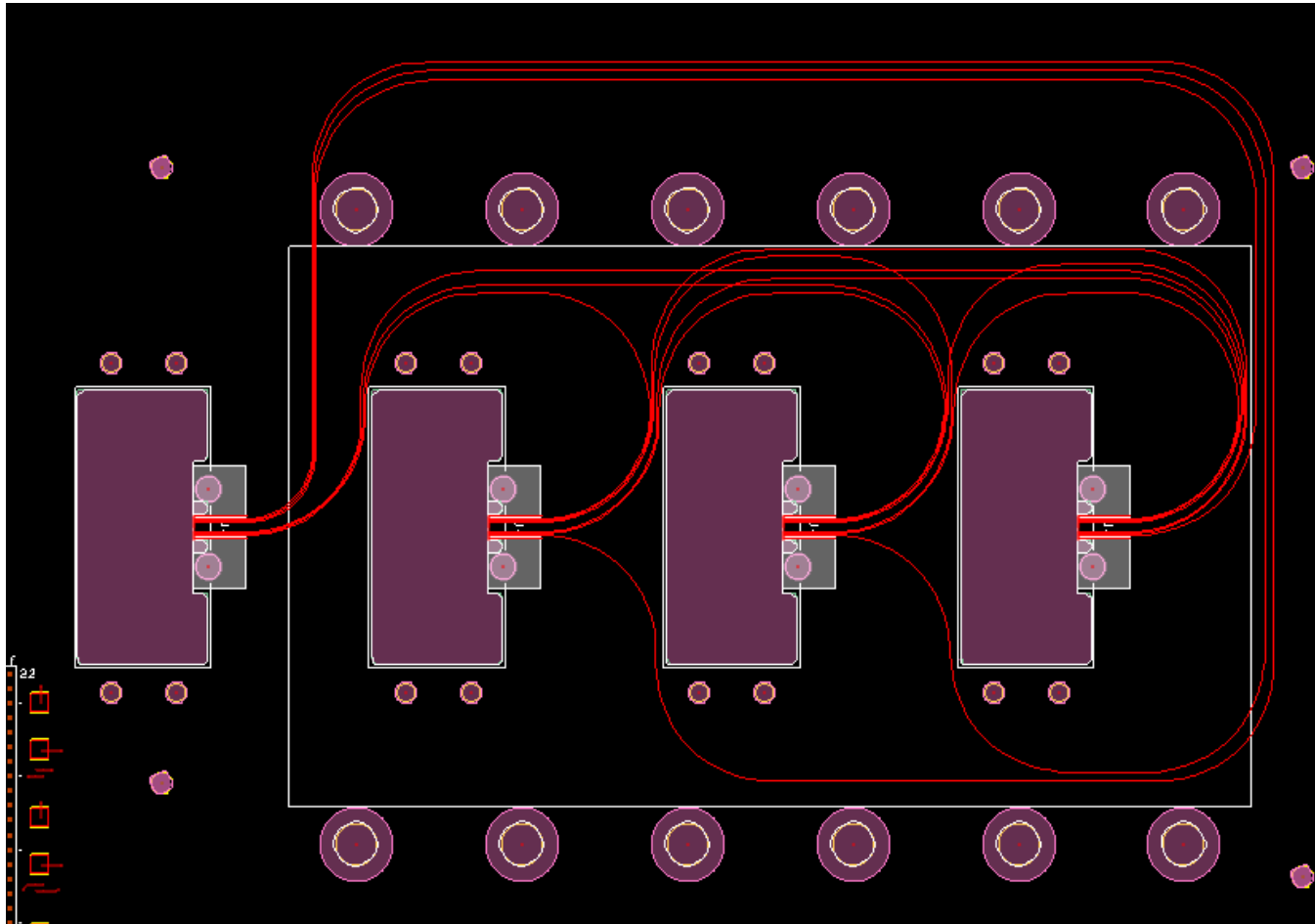
- Loss of 0.023 dB per 90° crossing consistent with other reports
- The output power dropped by 0.5% at each 90° crossing
- The loss per crossing (L_c) depends on crossing angle (θ), $L_c = 1.0779 \cdot \theta^{-0.8727}$

Loss of Waveguide Bends



Width (μm)	Optimum Radius (mm)	Maximum Power (dB)
50	13.5	-0.74
75	15.3	-0.91
100	17.7	-1.18

System Demonstrator

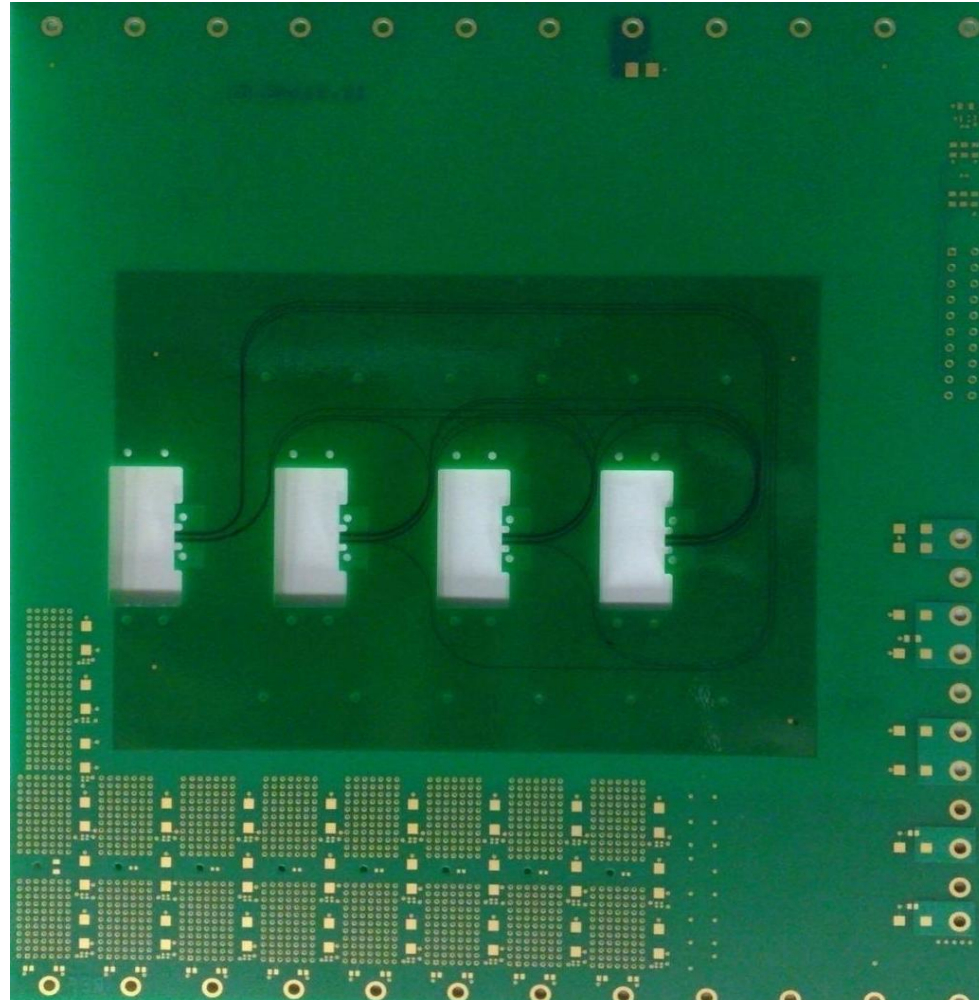


Fully connected waveguide layout using design rules

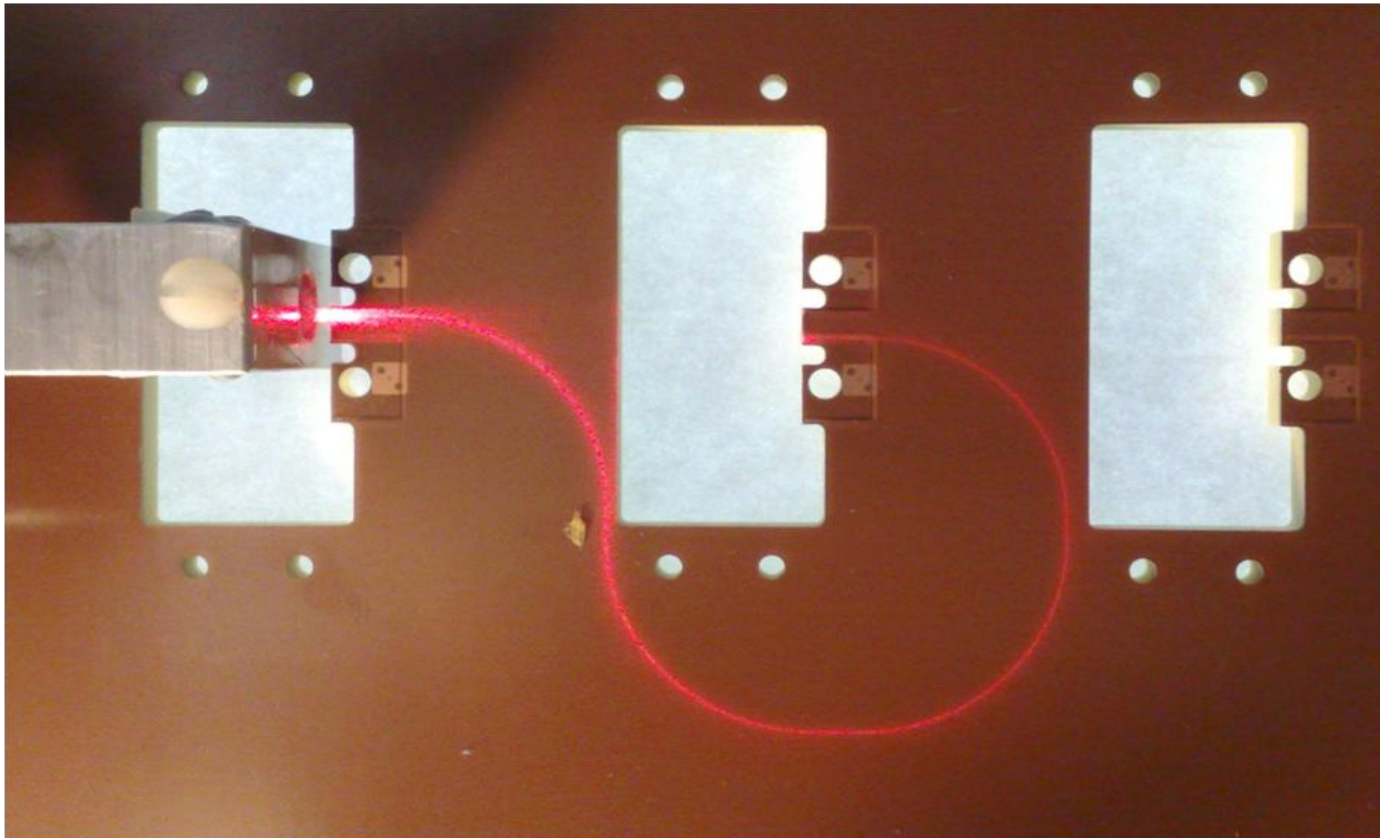
Power Budget

Input power (dBm/mW)	-2.07 / 0.62					
	Bend 90°					
Radii (mm)	15.000	15.250	15.500	15.725	16.000	16.250
Loss per bend (dB)	0.94	0.91	0.94	0.94	0.95	0.95
	Crossings					
Crossing angles (°)	22.27	29.45	36.23	42.10	47.36	
Loss per crossing (dB)	0.078	0.056	0.047	0.041	0.037	
Min. detectable power (dBm)	-15 / 0.03					
Min. power no bit error rate	-12 / 0.06					

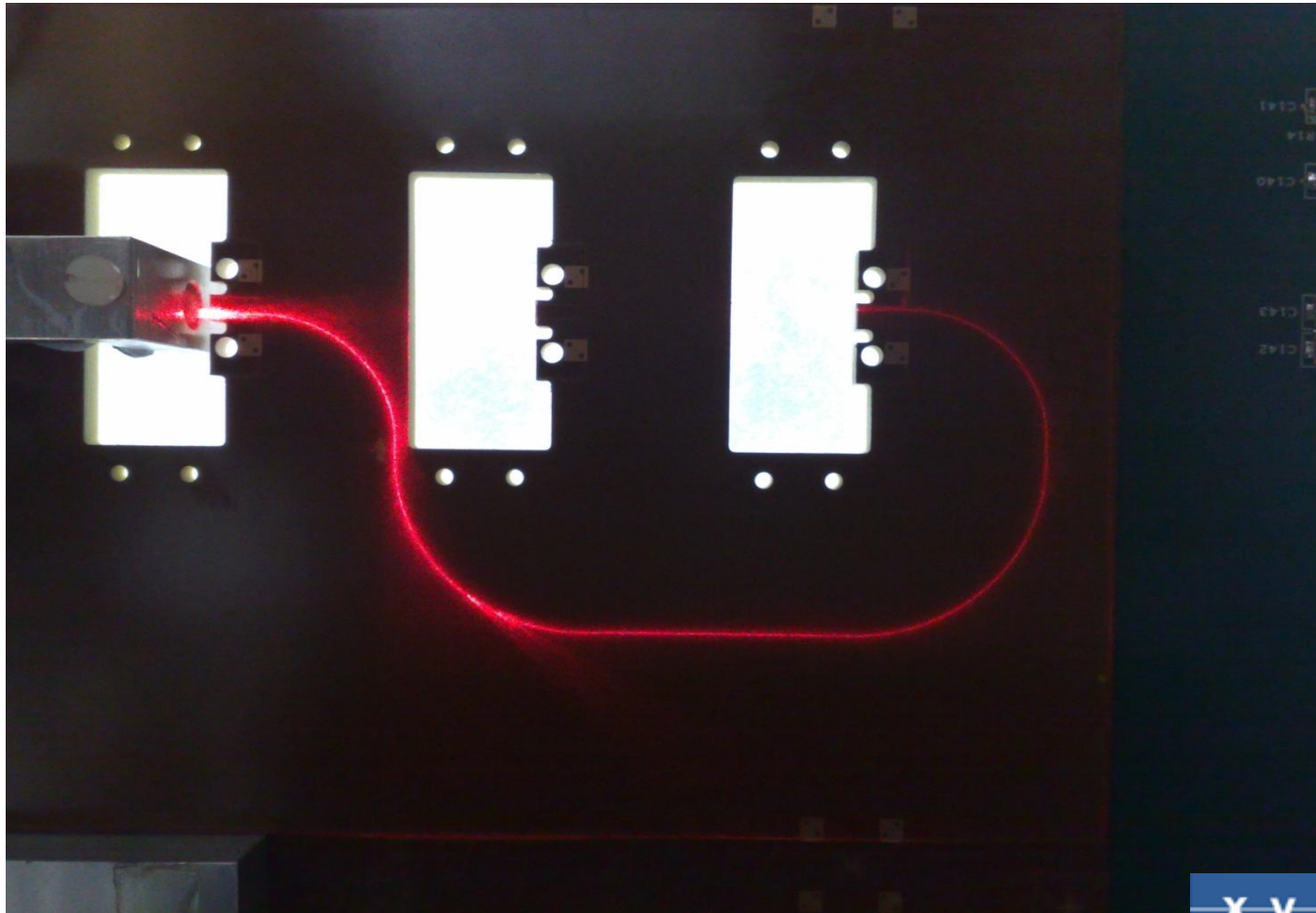
Demonstrator Dummy Board



The Shortest Waveguide Illuminated by Red Laser

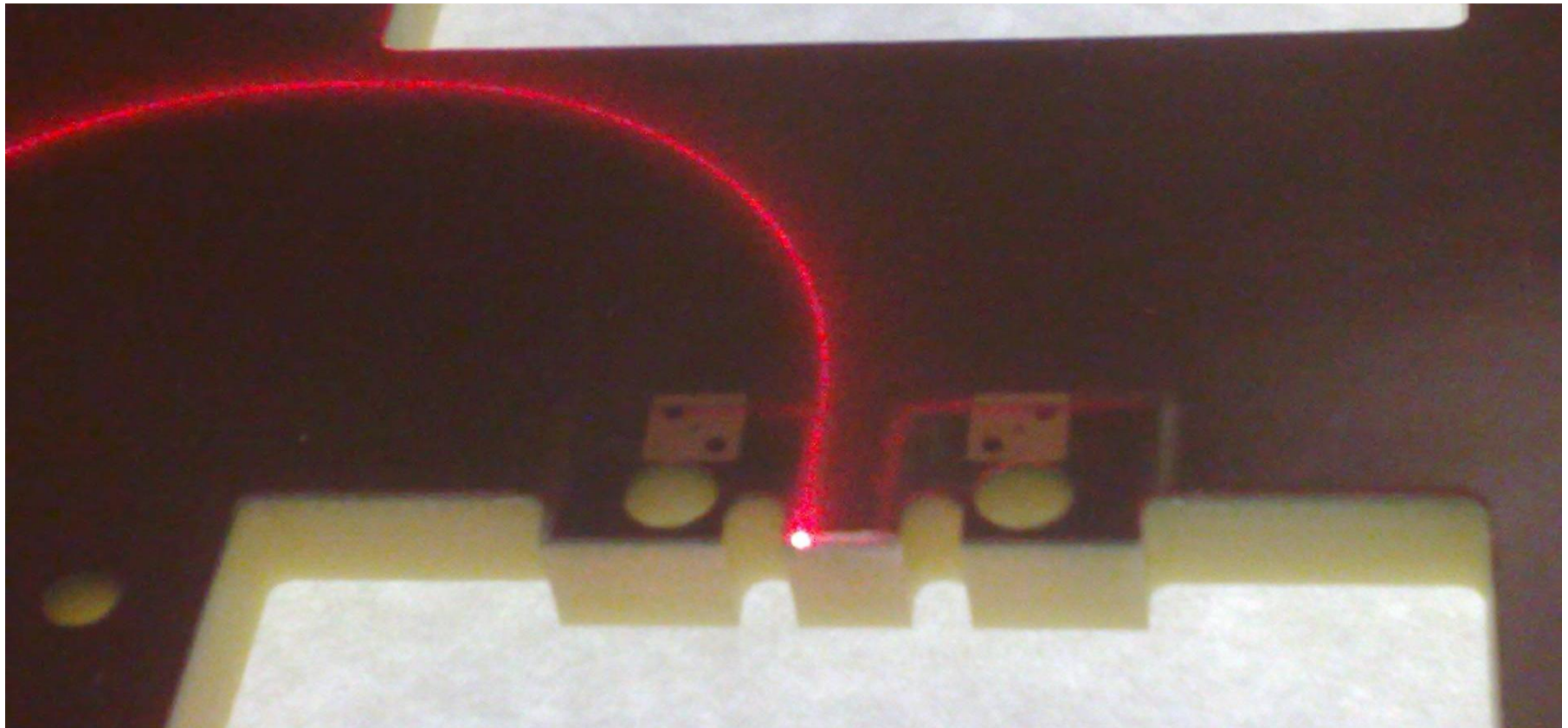


Waveguide with 2 Crossings Connected 1st to 3rd Linecard Interconnect



x-y-r-a-t-e-x

Output Facet of the Waveguide Interconnection



Data storage protocol and form factor trends

Disk drive form factors decreasing

3.5" HDD



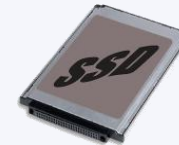
2.5" HDD



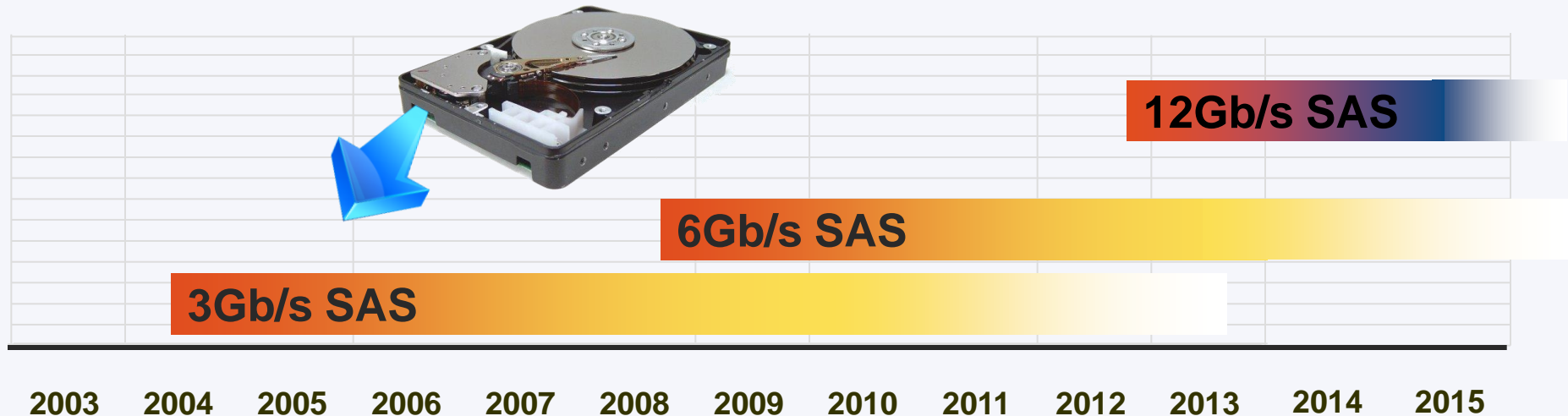
2.5" SSD



1.8" SSD



Data storage interconnect speeds increasing

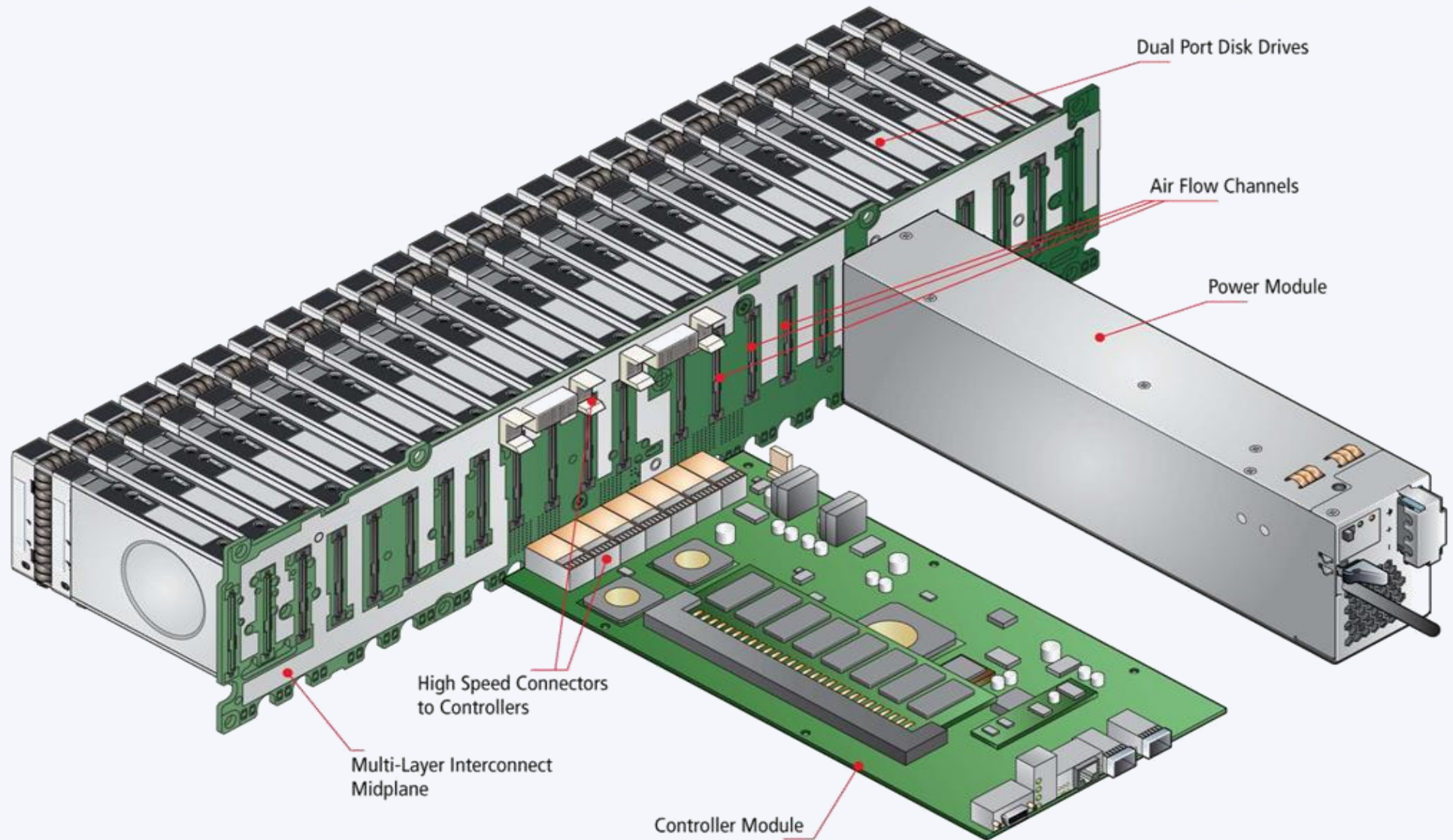


Source: SCSI Trade Association Sep 08

www.scsita.org



Design and performance constraints



ELECTRO-OPTICAL BACKPLANE

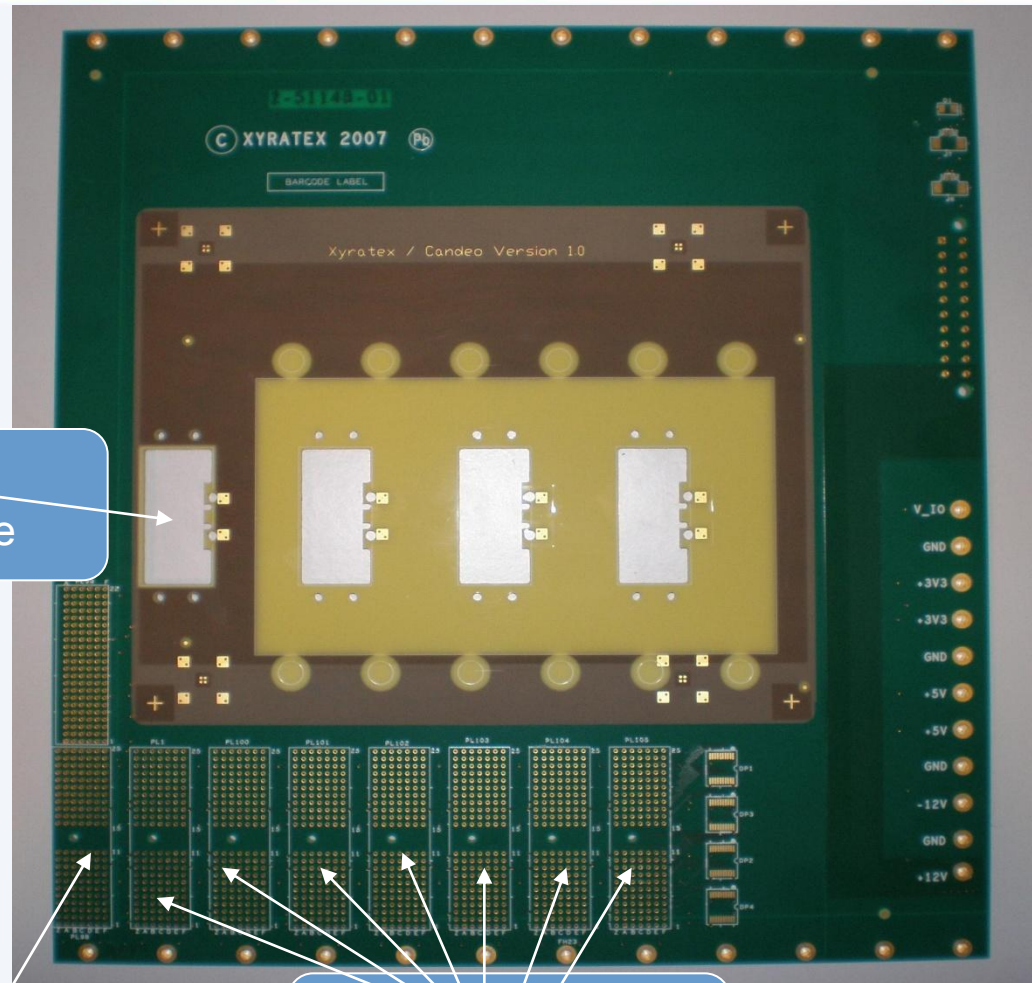
Hybrid Electro-Optical Printed Circuit Board

- ❑ Standard Compact PCI backplane architecture
- ❑ 12 electrical layers for power and C-PCI signal bus and peripheral connections
- ❑ Electrical C-PCI connector slots for SBC and line cards
- ❑ 1 polymeric optical layer for high speed 10 GbE traffic
- ❑ 4 optical connector sites
- ❑ Dedicated point-to-point optical waveguide architecture

Optical connector site

Compact PCI slot for single board computer

Compact PCI slots for line cards

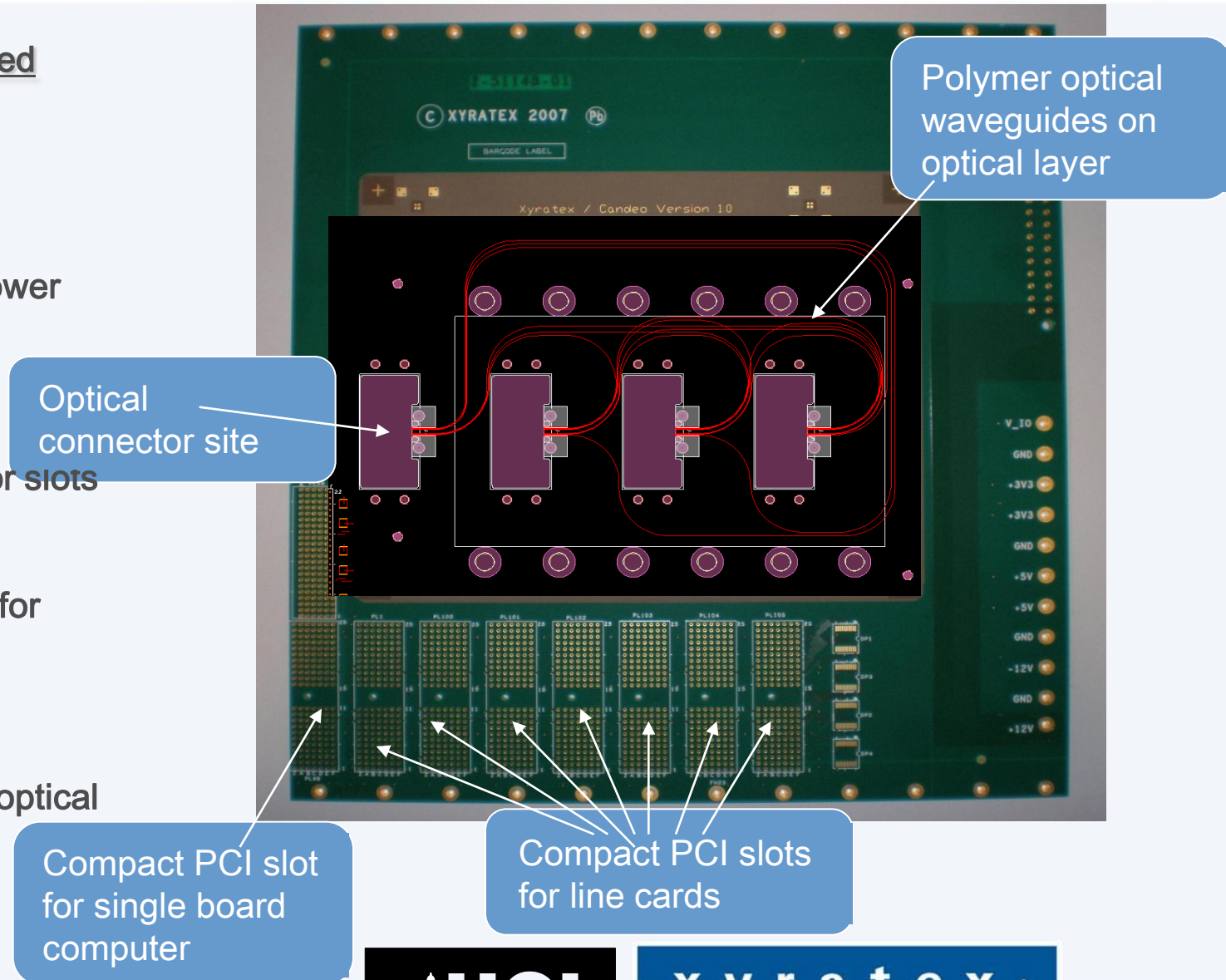


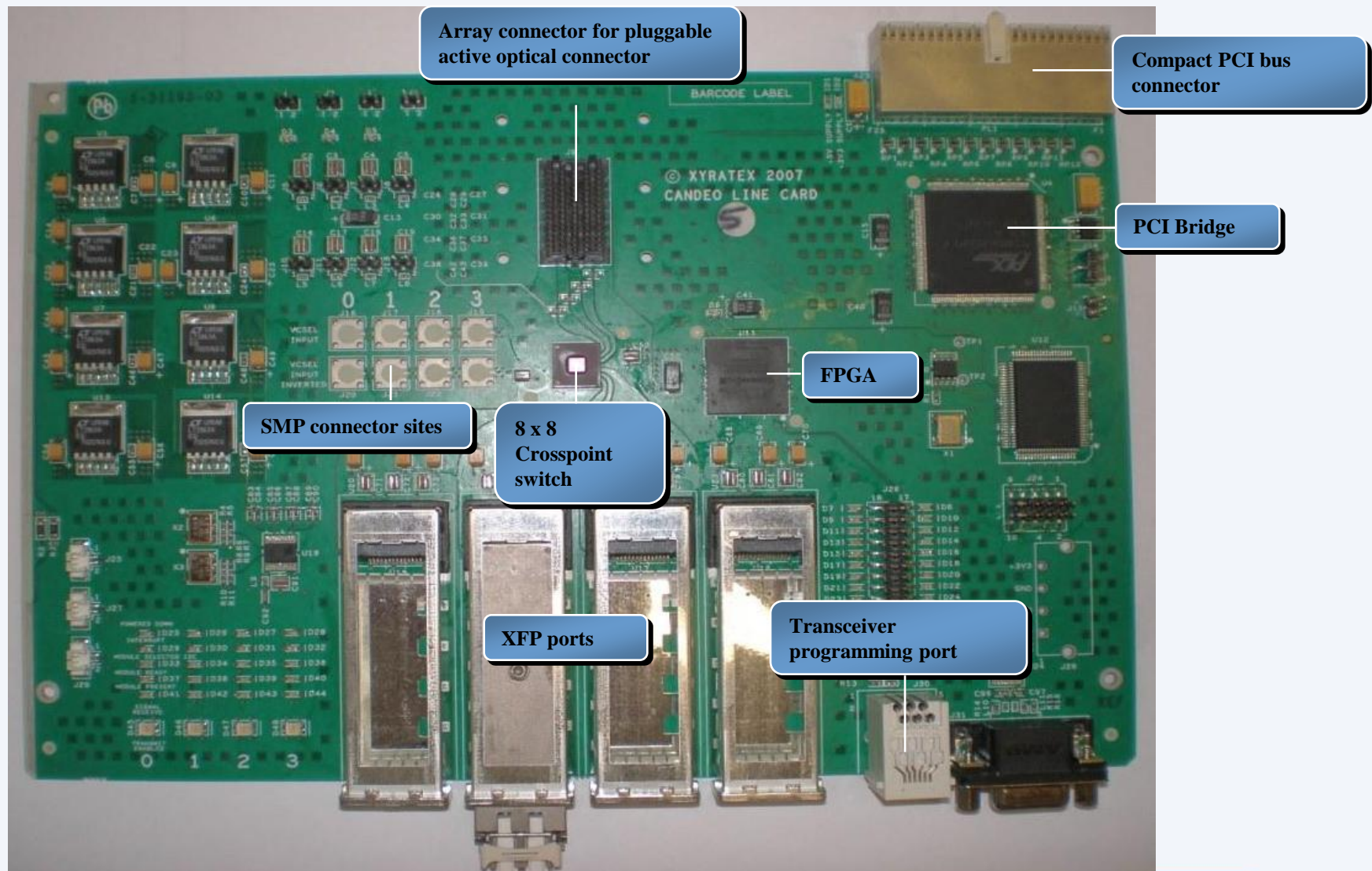
x y r a t e x

ELECTRO-OPTICAL BACKPLANE

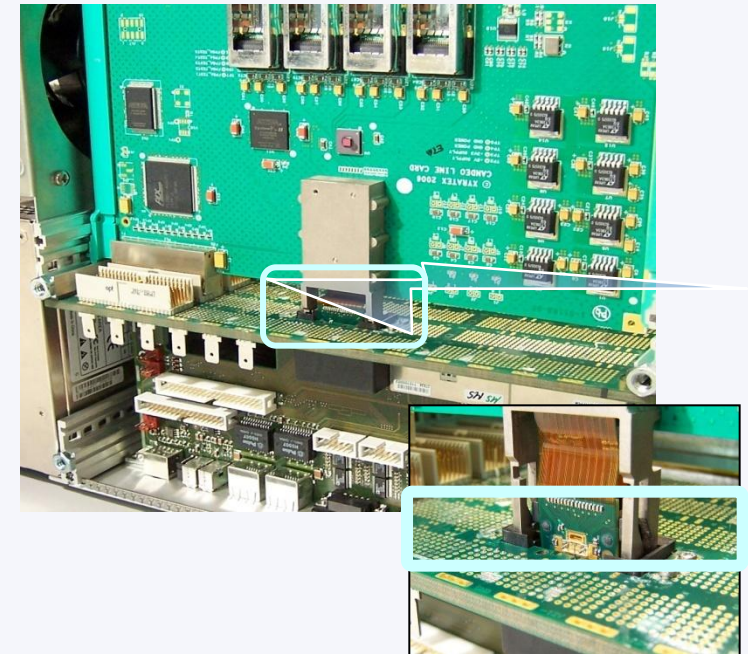
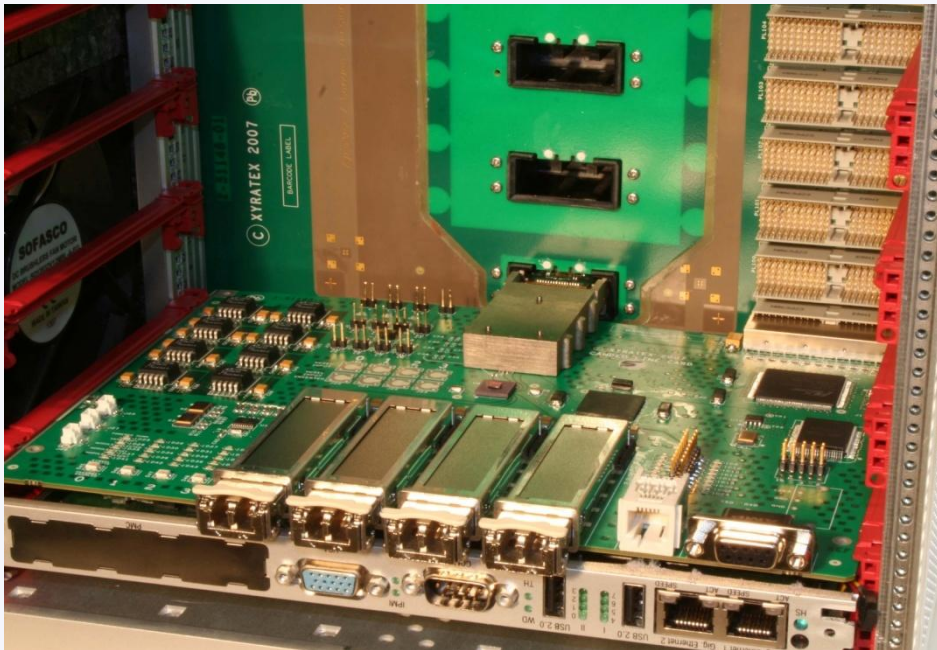
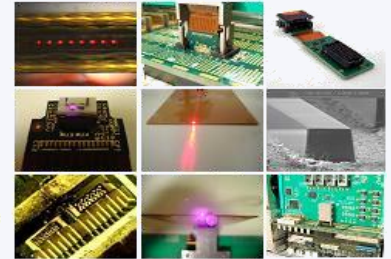
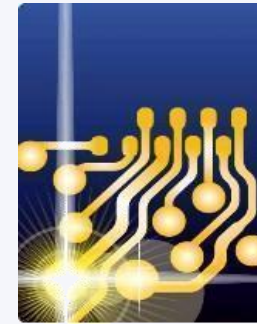
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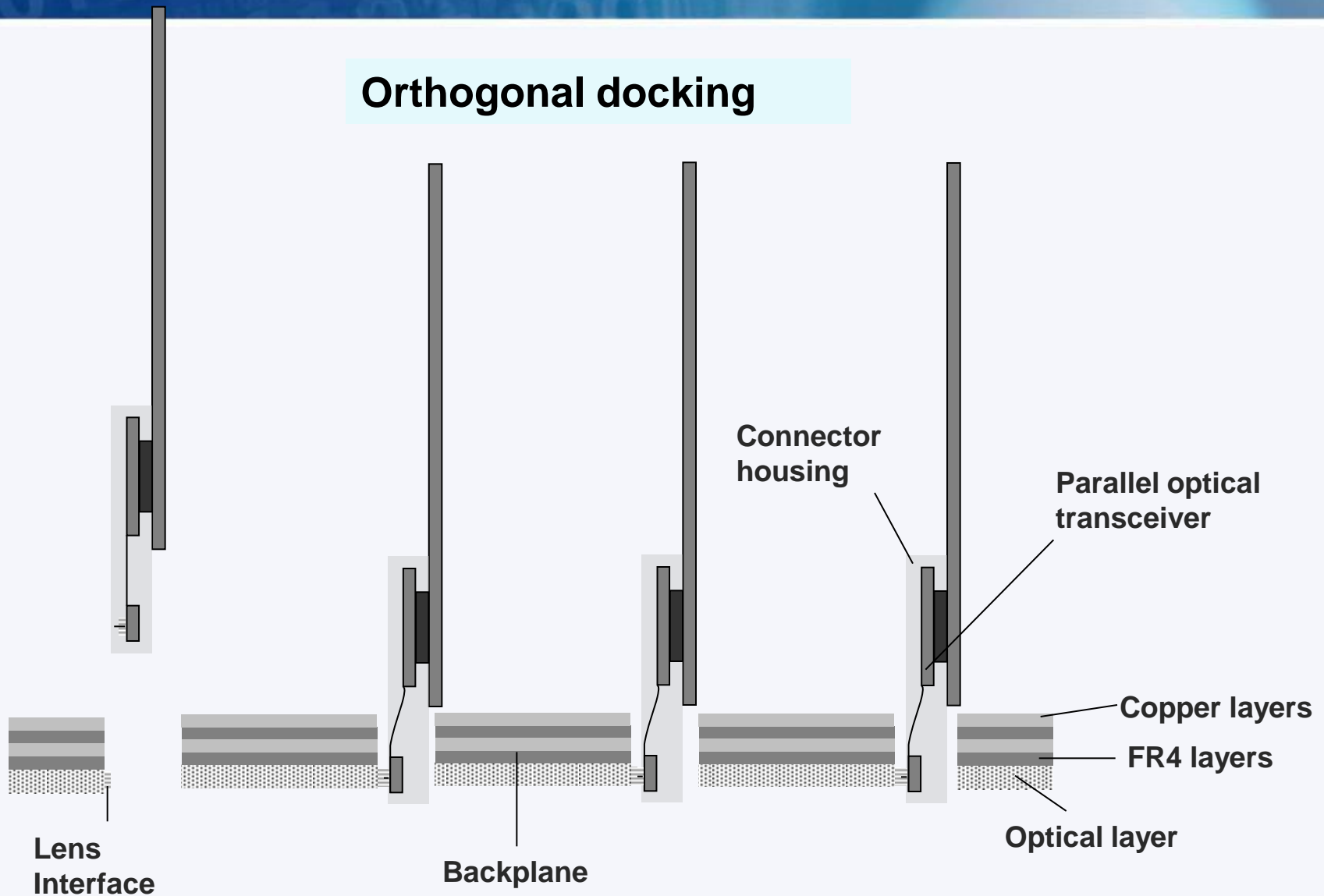




Active optical backplane connector

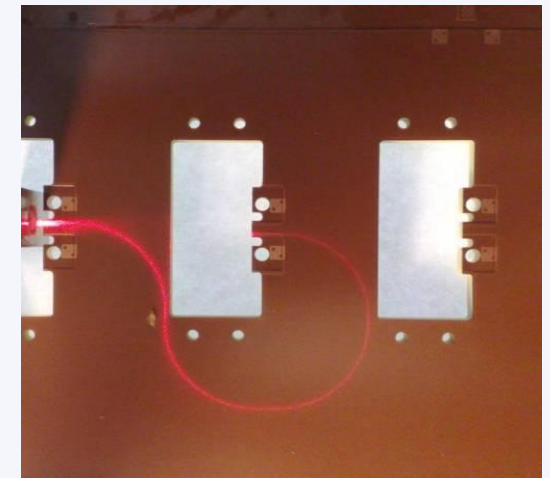
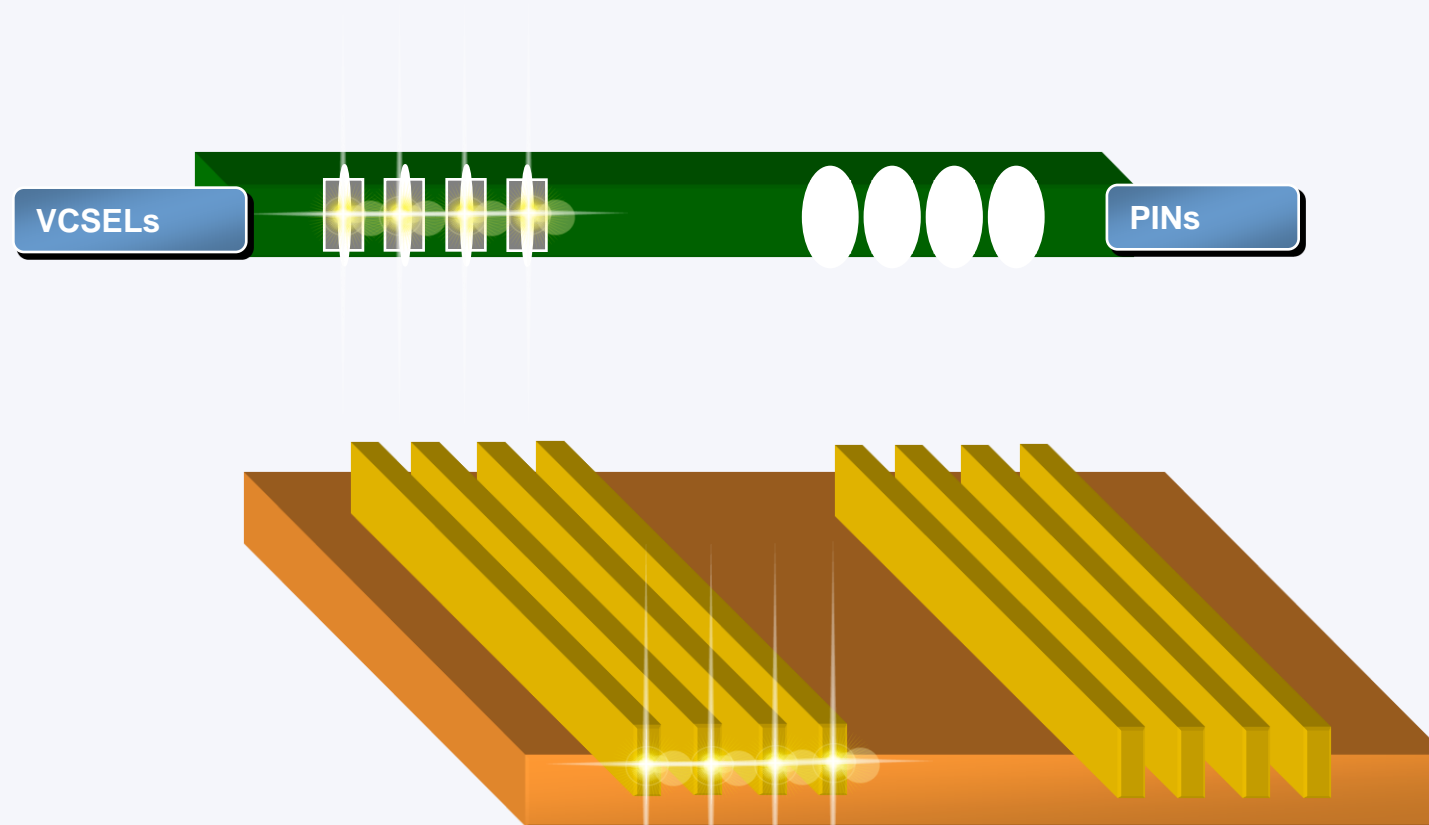


Optical backplane connection architecture



Optical backplane connection architecture

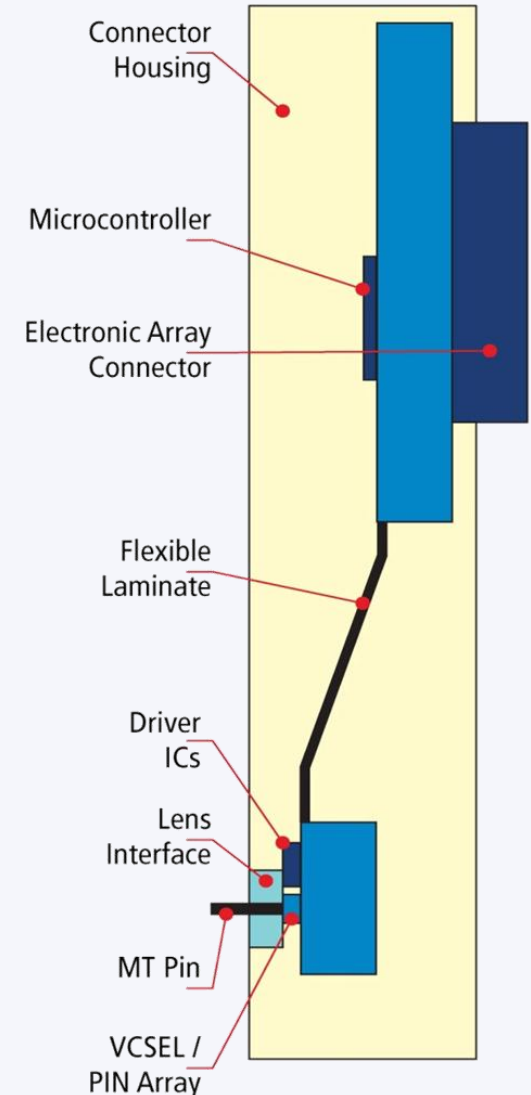
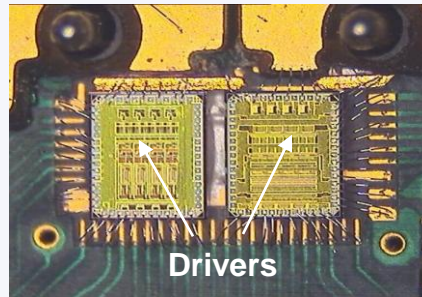
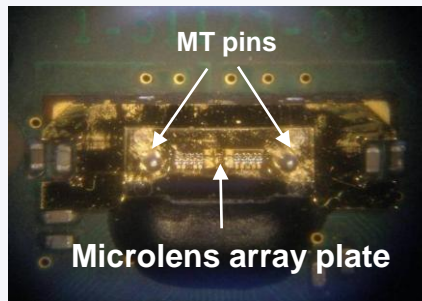
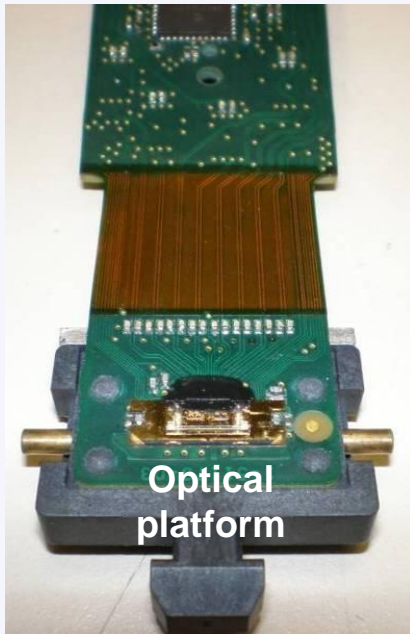
Butt-coupled in-plane connection



Single waveguide
illuminated

Parallel optical transceiver

- ❑ Mechanically flexible optical platform
- ❑ MT compatible optical interface
- ❑ Geometric microlens array
- ❑ Quad VCSEL driver and TIA/LA
- ❑ VCSEL / PIN arrays on pre-aligned frame



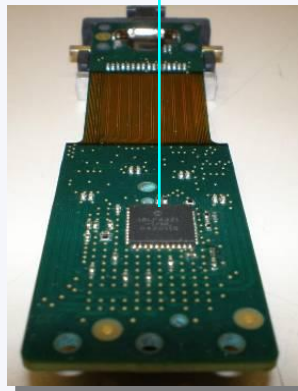
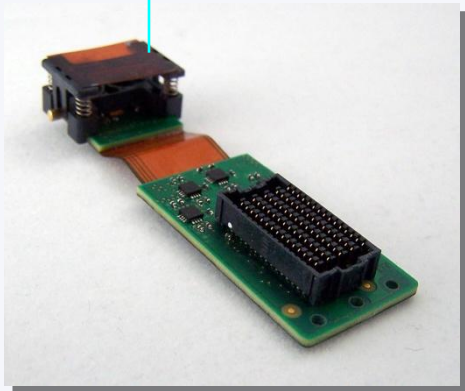
Active pluggable connector

Parallel optical transceiver

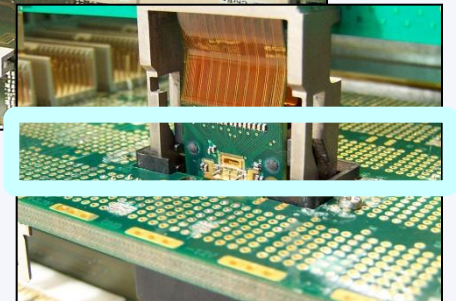
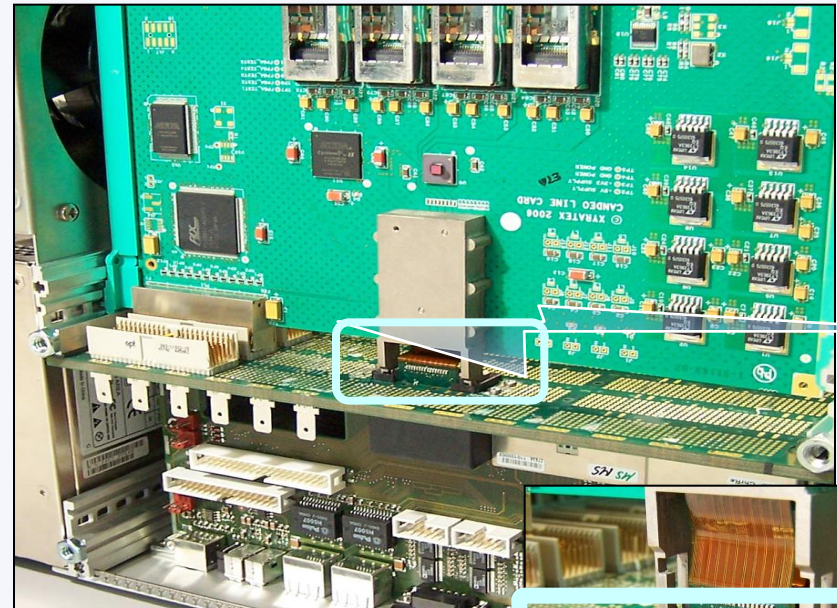


Spring loaded platform

Microcontroller

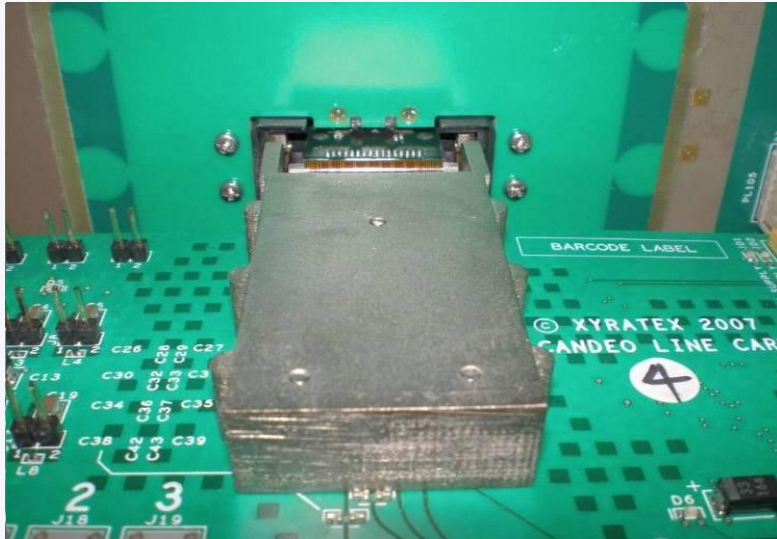


Connector module

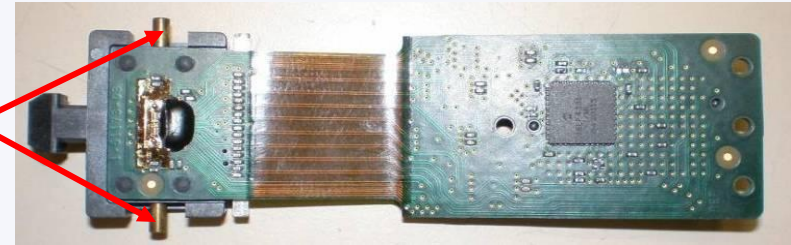


Connector engagement mechanism

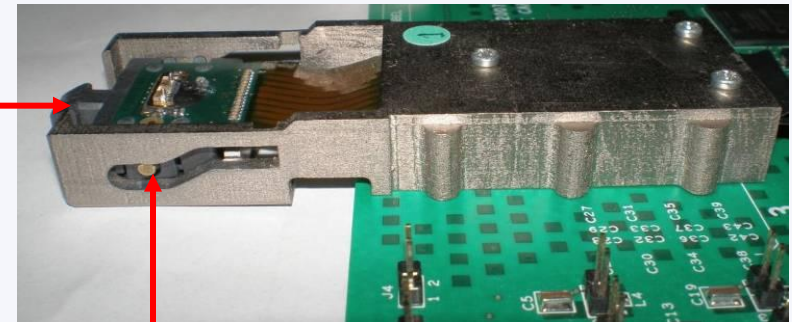
Docked



**Cam
followers**

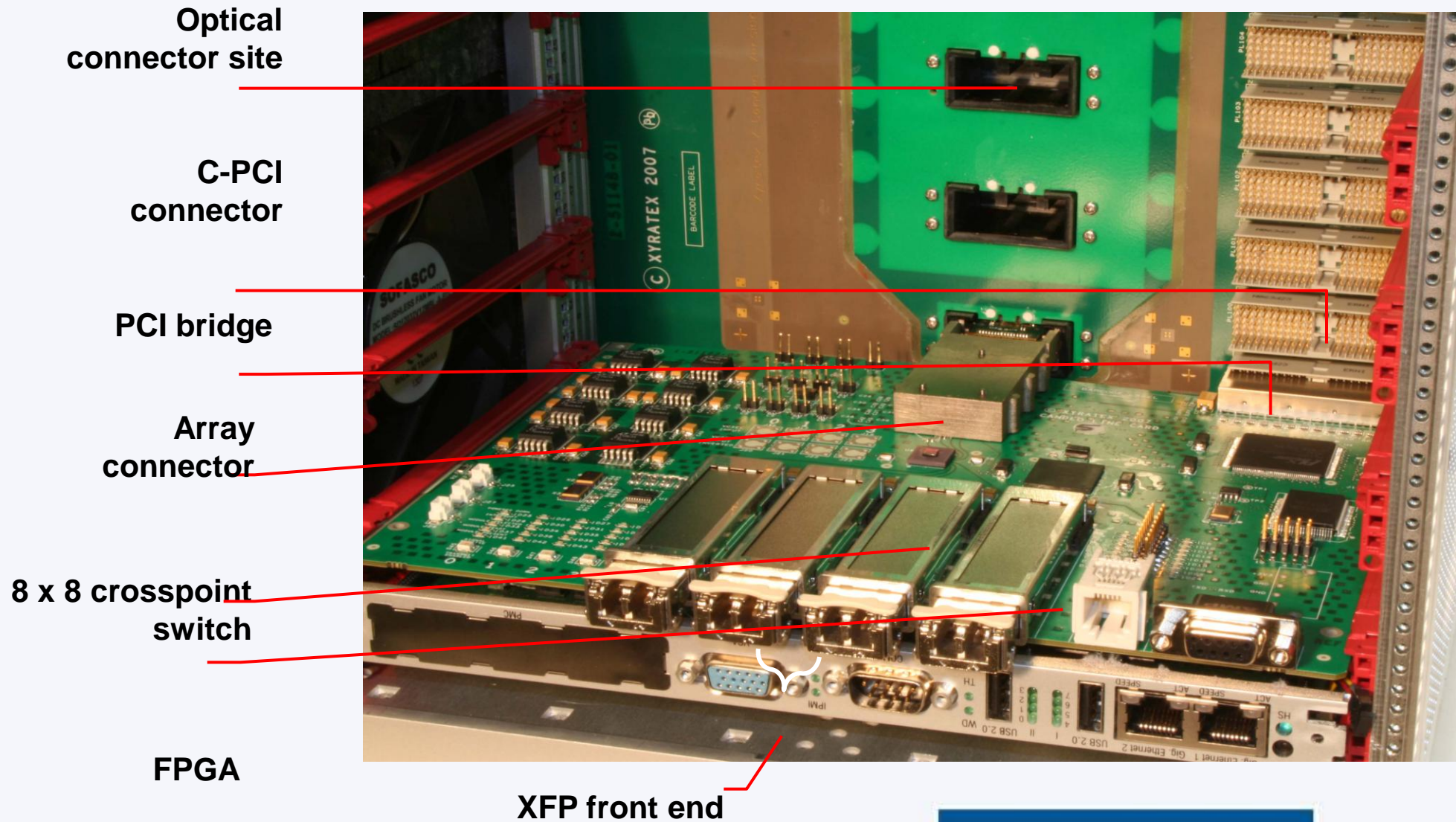


**Ramped
plug**



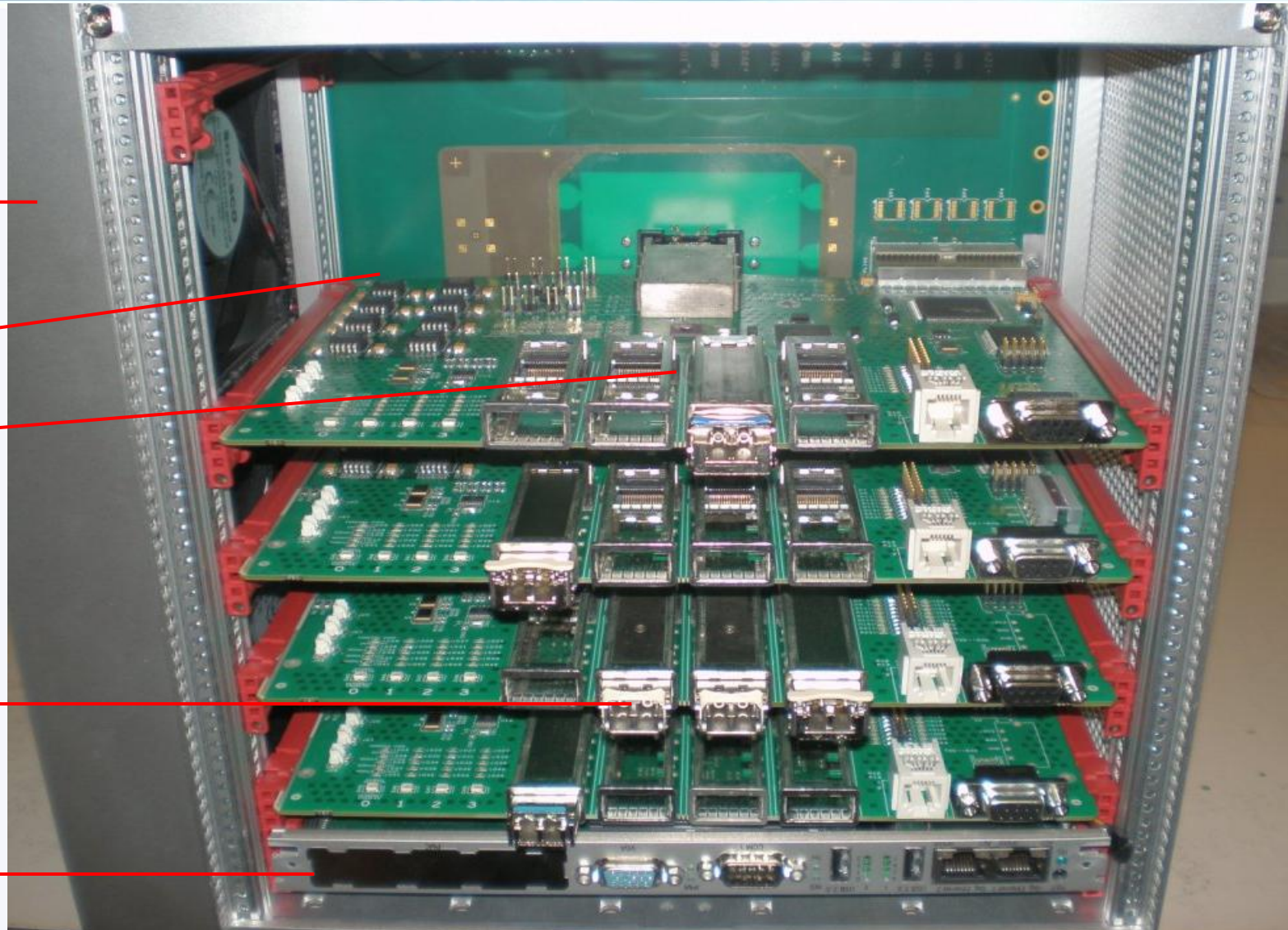
Cam track

Peripheral test cards

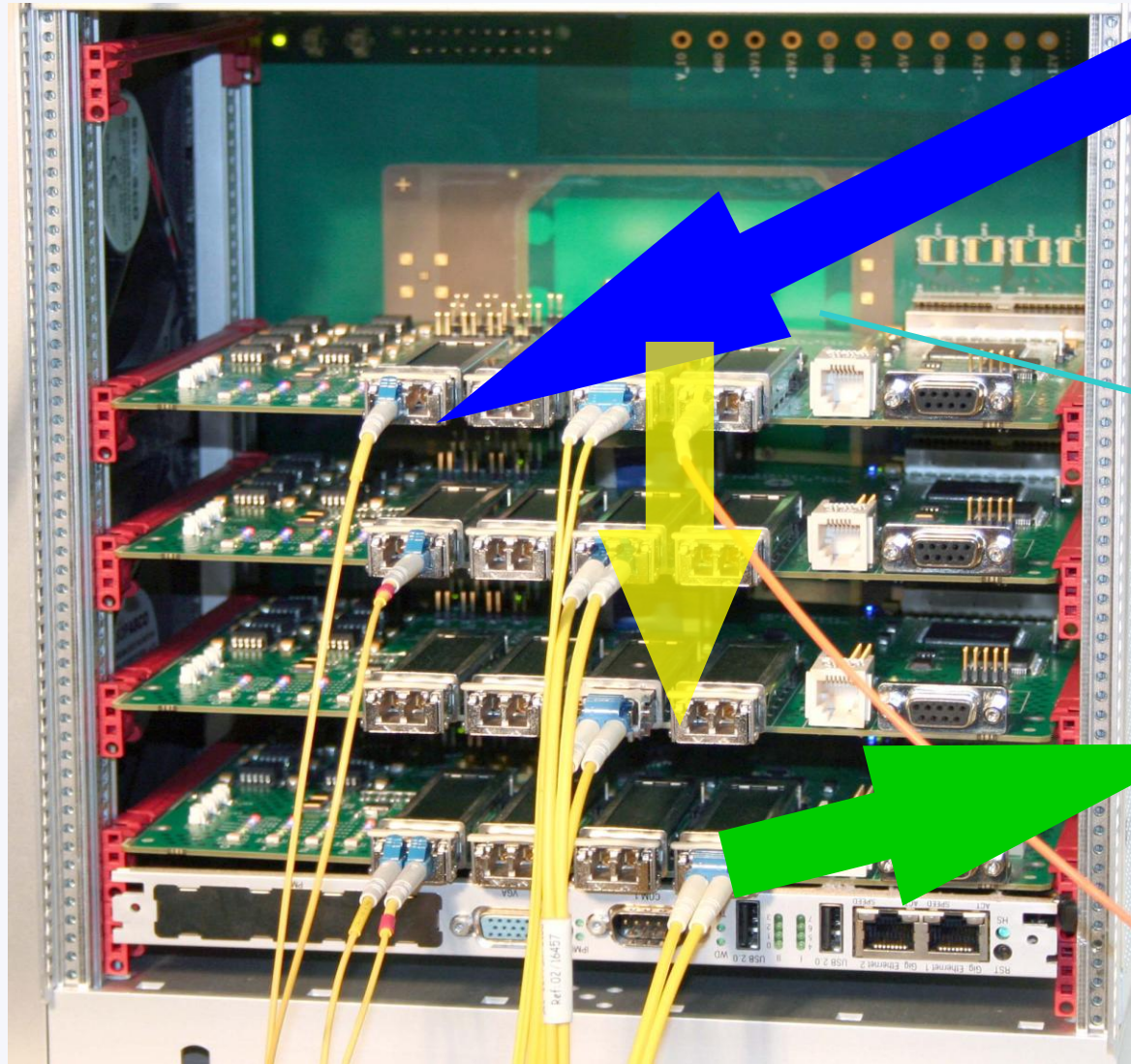


Demonstration platform

- Compact PCI chassis
- Electro-optical midplane
- Pluggable optical connector
- Peripheral test card
- Single board computer



High speed data transmission measurements



1st test card

- ☐ 10 GbE LAN test data
- ☐ Injected into front end

Electro-optical midplane

- ☐ Pluggable connectors
- ☐ Polymer waveguides

Target test card

- ☐ Retrieved through front end
- ☐ Signal integrity measured

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- **Cadence**
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